FEAMAC/CARES Software Coupling Development Effort for CMC Stochastic-Strength-Based Damage Simulation

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CARES: Ceramics Analysis and Reliability Evaluation of Structures

MAC/GMC: Micromechanics Analysis Code/ Generalized Method of Cells

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Scope and Technical Challenge

➢ Predict the strength and service life of ceramic ***& composite structures***

CMC - ***C***eramic ***M***atrix ***C***omposites & ***PMC*** - ***P***olymer ***M***atrix ***C***omposites

- **Need to account for:**
  - Wide variability in the strength of individual components (probabilistic/stochastic strength)
  - How strength changes with different types of loading (strength vs: multiaxial loading) and size of the structure (size-effect)
  - How strength degrades with time and fluctuating load
  - How strength/damage response of monolithic, anisotropic and composite material (architectures) differ

Approach / Outline

1. Overview: Describe the MAC and CARES codes

– **MAC/GMC:** composite ***micromechanics*** model

– **CARES Unit Sphere:** multiaxial ***stochastic strength*** model
(isotropy & anisotropy)

2. Applying CARES to the MAC code to simulate stochastic damage progression in a ceramic matrix composite (CMC)

❖ ***Cellular Automaton***: Encouraging failure of adjacent elements - mimics crack-like growth

❖ Visualization of element-by-element failure propagation for fiber, matrix, and interface

– **Status & Capability:** Current progress of code integration effort

➢ **Examples:**

(1) Stress-strain response of a SiC-RBSN laminate (circa 1990)

(2) Time-dependent degradation notional example

MAC/GMC Methodology: Generalized Method of Cells (*GMC*) & High-Fidelity Generalized Method of Cells (*HFGMC*)

❖ ***Micromechanics links the size scales &** provides the composite response based on the composite constituent materials*

▪ ***FEAMAC:** MAC/GMC embedded in FEA as constitutive material*

GMC (1990s)

- 1st order displacement field in subcells
- Stresses and strains piecewise constant
- Number of linear algebraic equations function of number of subcells
- Local inelasticity/damage
- *No shear coupling*
- No "*subcell mesh*" sensitivity

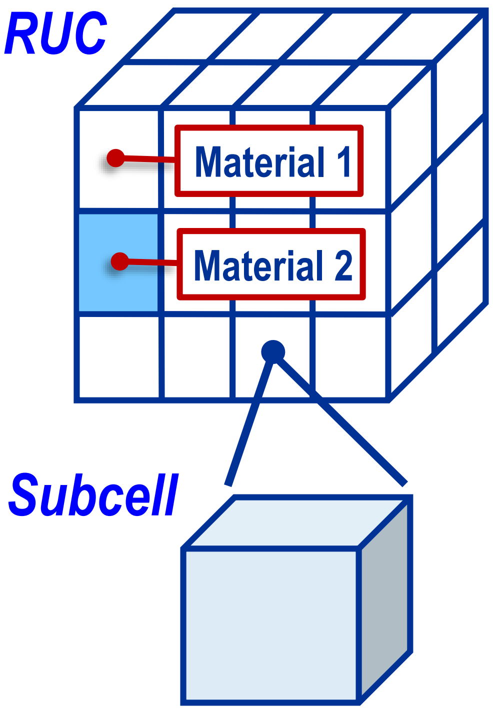
HFGMC (2000s)

- 2nd order displacement field in subcells
- Elastic stresses and strains piecewise linear
- Number of linear algebraic equations is rather large
- Local inelasticity/damage
- *Has shear coupling*
- Has "*subcell mesh*" sensitivity

Repeating Unit Cell (RUC) of composite material

❖ RUC made subcells

❖ Multiscale capability



We currently only use GMC in FEAMAC/CARES

Aboudi, J.; Arnold, S.M.; and Bednarcyk, B.A. (2013) Micromechanics of Composite Materials: A Generalized Multiscale Analysis Approach, Elsevier, Oxford, UK.

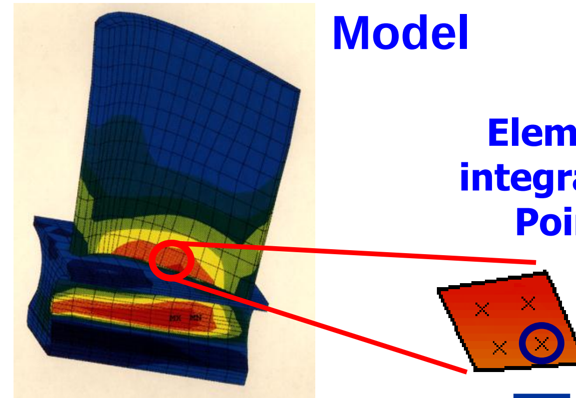
Aboudi, J; Pindera, M.J.; and Arnold, S.M. (2003): Higher-Order Theory for Periodic Multiphase Materials With Inelastic Phases. Int. J. Plast., vol. 19, pp. 805–847.

CARES: Ceramics Analysis and Reliability Evaluation of Structures

Life Prediction & Component Design Code For Advanced Ceramics

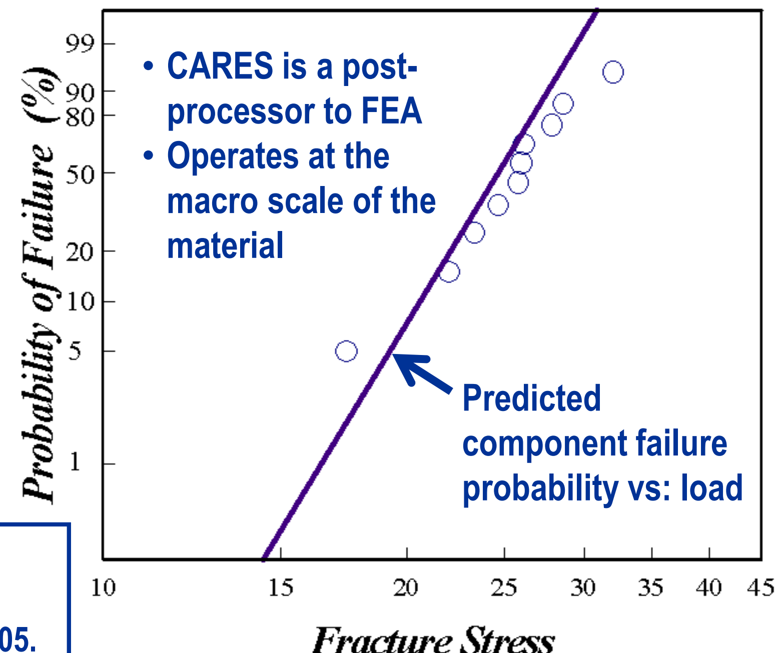
- Developed to predict the probability of failure of ceramic components under complex thermomechanical loading
- Combines Weibull & Weakest Link theory with concepts of linear elastic fracture mechanics (the ***Unit Sphere*** model)

Structural Model



Element integration Point

(CARES) reliability analysis



Component Reliability Analysis Capability:

- Transient loads and temperatures
- Fast-Fracture Rupture
- Time-dependent (da/dt) crack growth
- Cycle-dependent (da/dn) crack growth
- Multiaxial stress failure models
  *(PIA & **Unit Sphere** & Tsai-Wu & Tsai-Hill)*
- Proof test

Nemeth, Jadaan, Gyekenyesi.: "Lifetime Reliability Prediction of Ceramic Structures Under Transient Thermomechanical Loads." NASA/TP-2005-212505, 2005.

Approach for Life Prediction & Component Design of Composites

➢ *Combine CARES, MAC & FEA codes*

Move CARES from the macroscopic scale of the structure to the microscale of the individual RUC material constituents

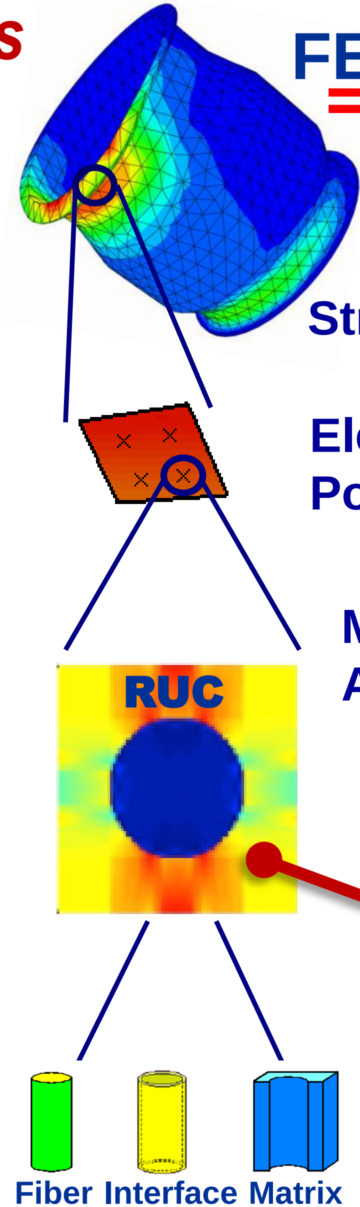
❖ FEAMAC/CARES Capability:

- Individual constituent and component level probability of failure tracked (for failure initiation)
- Individual & concurrent failure modes
- Laminate level analysis capability
- Progressive damage capability/simulation
  - ➢ Subcells killed at random failure thresholds

Debonding/crack path physics at constituent level not explicitly included

FEAMAC/CARES

{ Abaqus UMAT *"User Material"* }



Structural-Scale FEA

Element/Integration Point

Micromechanics Analysis

(MAC/GMC)

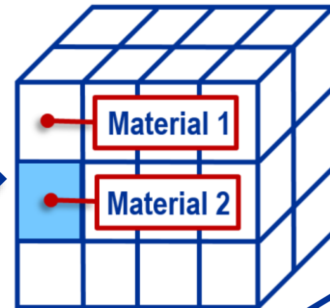
(CARES) Subroutine

Reliability analysis at the RUC level

Progressive Damage Criterion

Calculate failure probability, P_f , <u>for each material constituent of the RUC</u> associated with an element integration point

CARES calculated
$P_{f\,(CARES)}$ of RUC



RUC

Random number generated
$P_{f(Random)}$ of RUC

$$P_{f\,(CARES)} \geq P_{f\,(Random)}$$

Yes

Fail *all* material constituent subcells
➢ *Kill elastic modulus*

No

Don't fail subcells

Encourages more rapid damage propagation than failing individual subcells

Random Element Failure vs: Neighbor Influenced Failure (Cellular Automaton Enhancement)

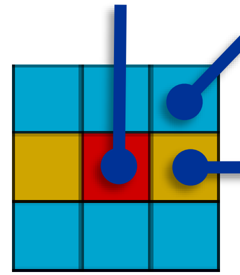
Encourage more abrupt failure and "crack-like" damage growth patterns

A cellular automaton is a collection of "colored" cells on a grid that evolves through discrete time steps according to a set of rules based on the states of neighboring cells

Rule: When failure of an element is encountered, the random failure threshold of the neighboring elements are adjusted to that of the failed element. *Load state determines which elements have highest probability of failure*

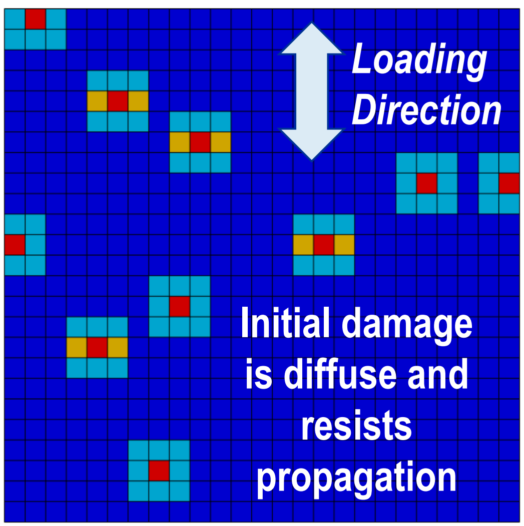
Failed element

Adjacent element



Adjacent 2 elements with highest $P_{f\ (CARES)}$ has $P_{f\ (Random)}$ adjusted

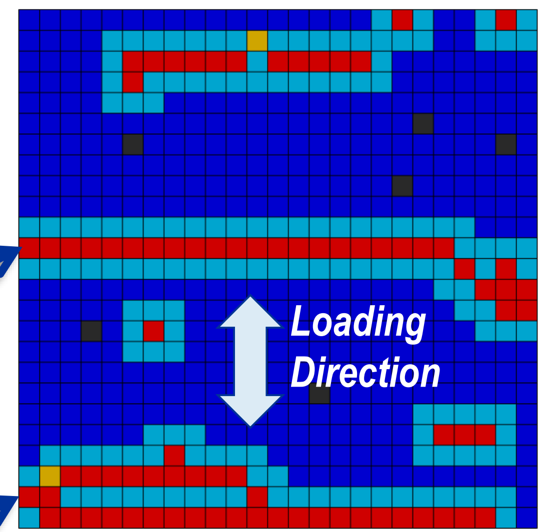
Random element failure



Example: 0^{o} Ply uniaxial ramp load 25x25 FEA mesh

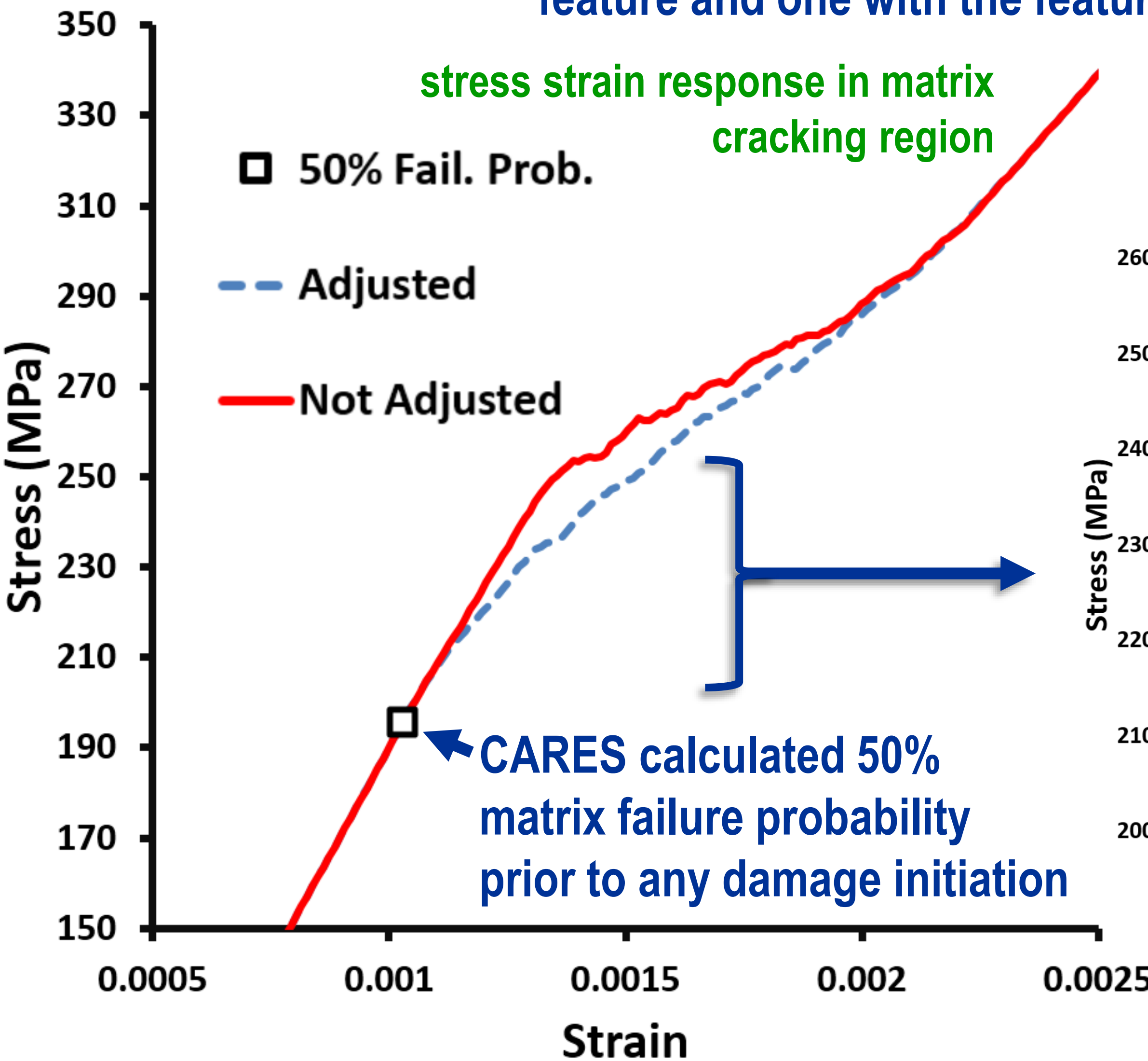
Adjusted element $P_{f\ (Random)}$ more likely to be lower than original $P_{f\ (Random)}$ and fail sooner as load increases – *enhancing damage propagation*

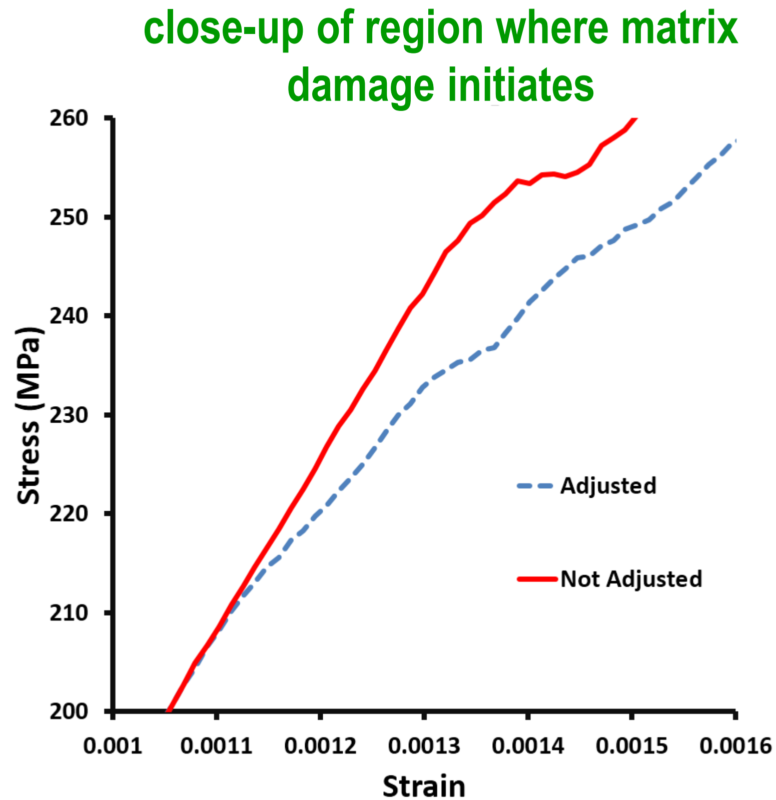
Cellular automaton



0º single ply tensile specimen *(Load parallel to fiber axis)*

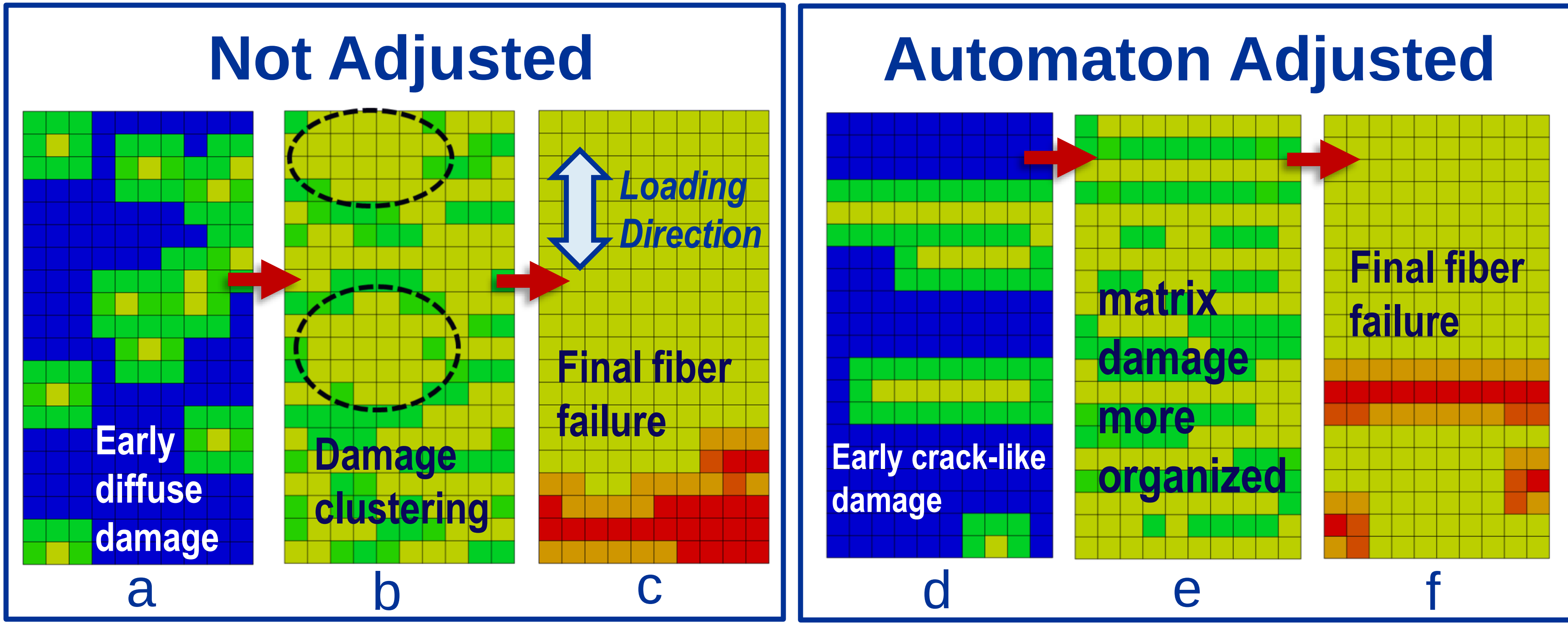
Shown are two trial executions; one using the automaton adjusted element feature and one with the feature inactive





0º single ply tensile specimen

Progression of damage in FE model of a unidirectional ply under longitudinal loading



Matrix failure
Fiber failure
No failure
Adjacent to failed matrix
Adjacent to failed fiber

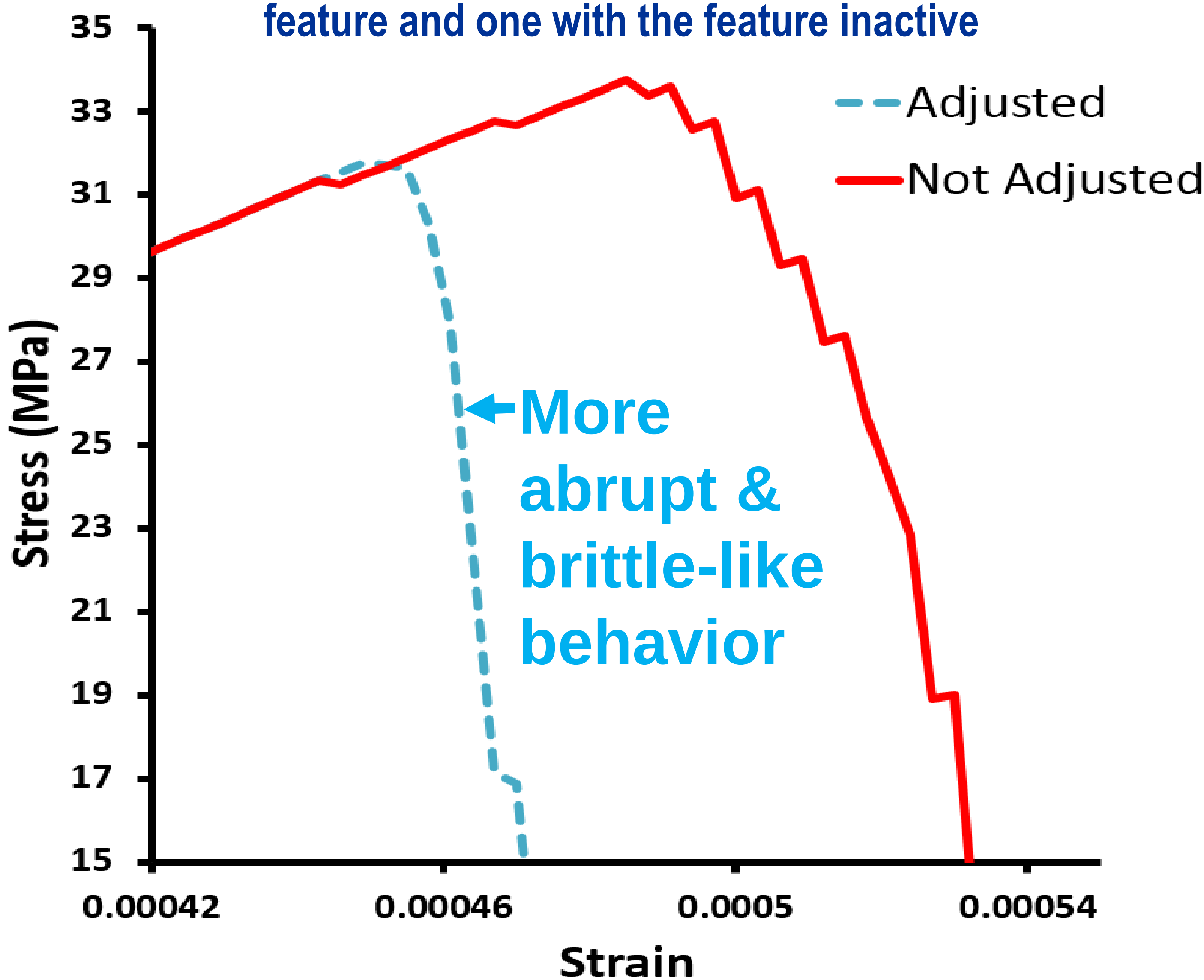
(a) and (d) ; early matrix damage

(b) and (e) ; progression to substantial matrix damage

(c) and (f) ; final composite failure (fiber failure)

90º single ply tensile specimen *(Load transverse to fiber axis)*

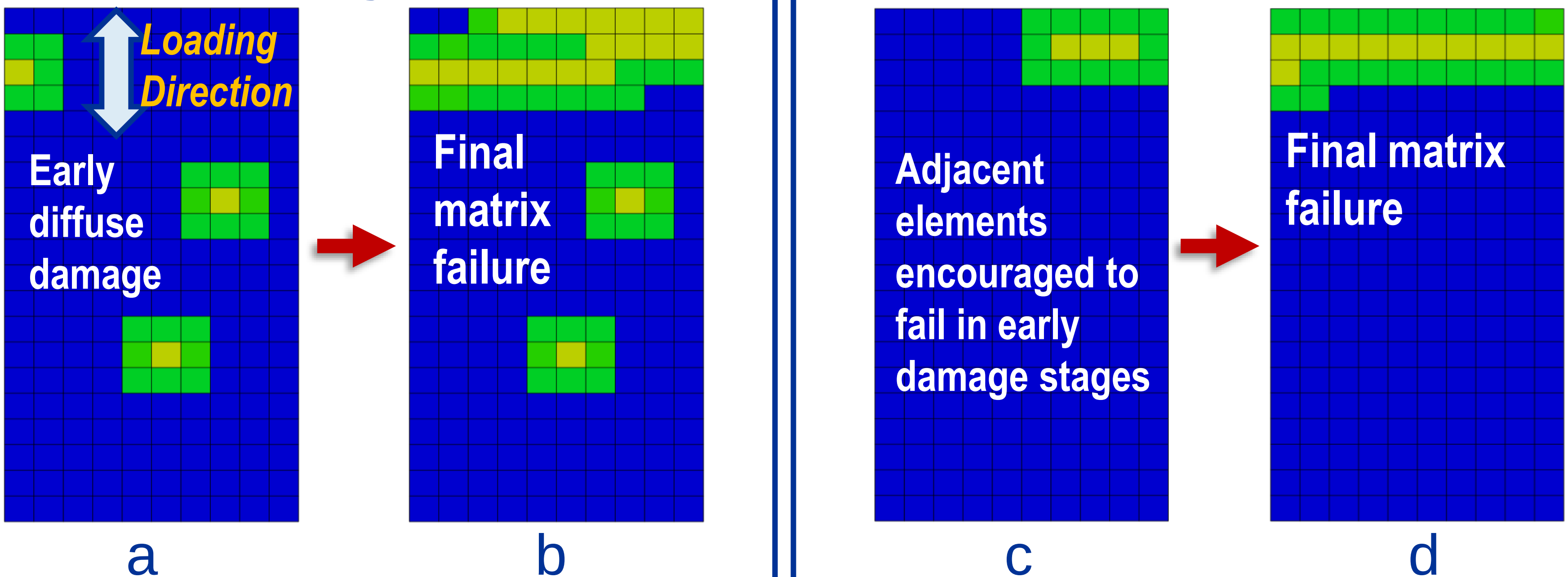
Shown are two trial executions; one using the automaton adjusted element feature and one with the feature inactive



90º single ply tensile specimen

Progression of damage in FE model of a unidirectional ply under *transverse* loading

Not Adjusted | **Automaton Adjusted**



- Matrix failure
- Adjacent to failed matrix
- No failure

(a) and (c) ; early matrix damage

(b) and (d) ; final composite failure (matrix failure)

Example: SiC/RBSN Laminated Composite in *On-Axis* & *Off-Axis* Loading

• **Tested by Bhatt & Phillips (1990)**

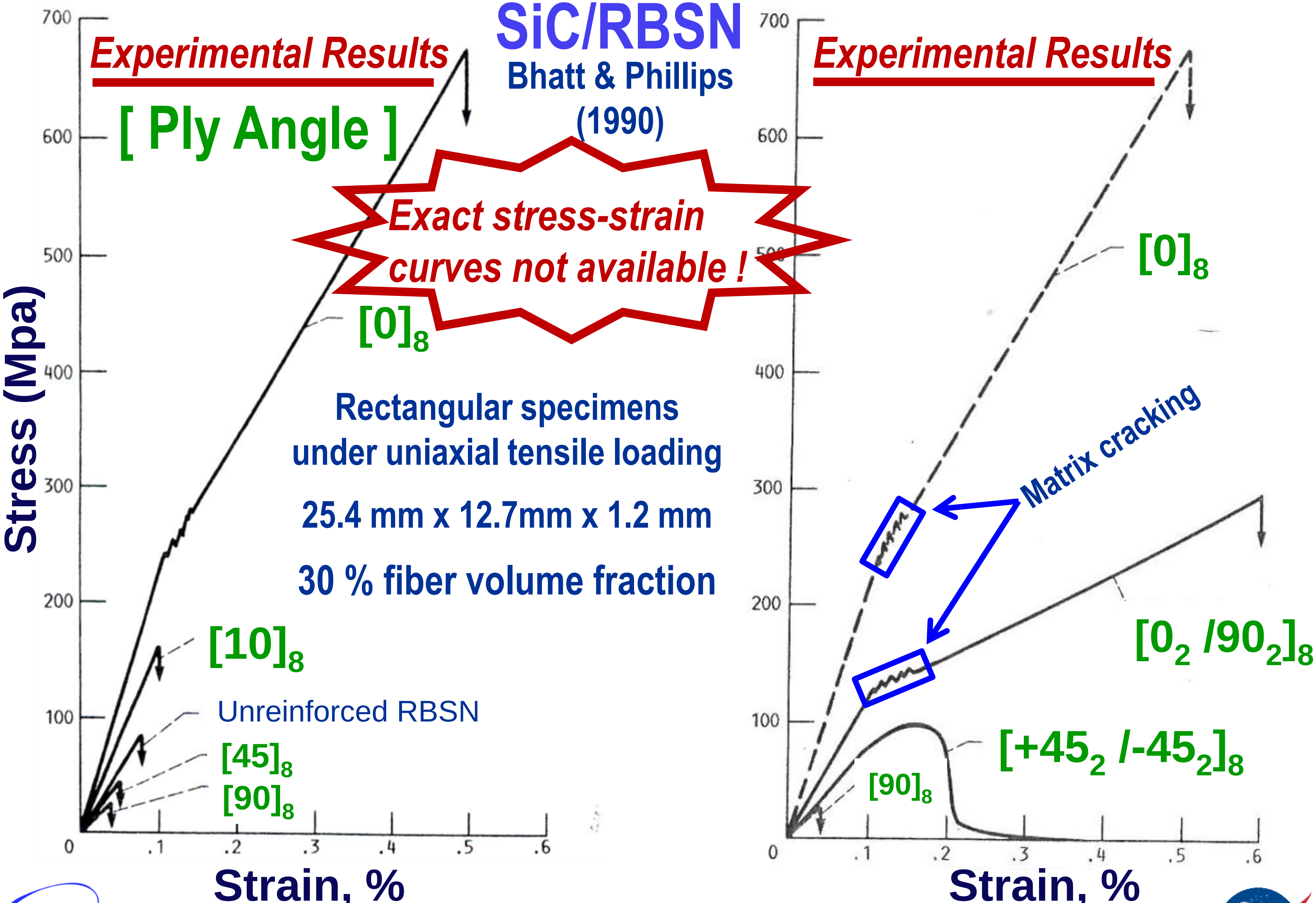
➢ **displays key mechanisms/features for model material**

- SCS-6 fiber/Reaction Bonded Silicon Nitride matrix composite examined in detail by NASA ➢ several papers published
- Laminated CMCs of interest to industry and less complex than woven composites
  ➢ failure modes are not conflicted with complex fiber architecture
- [0] & [0/90] laminates display nonlinearity due to matrix failure, followed by fiber failure.
- Remaining ply orientations display sudden brittle failure.

Bhatt, R.T., and Phillips, R.E.: "Laminate Behavior for SiC Fiber-Reiinforced Reaction-Bonded Silicon Nitride Matrix Composites." J. of Comp. Tech. & Res. V. 12, No. 1, Spring 1990, pp. 13-23.

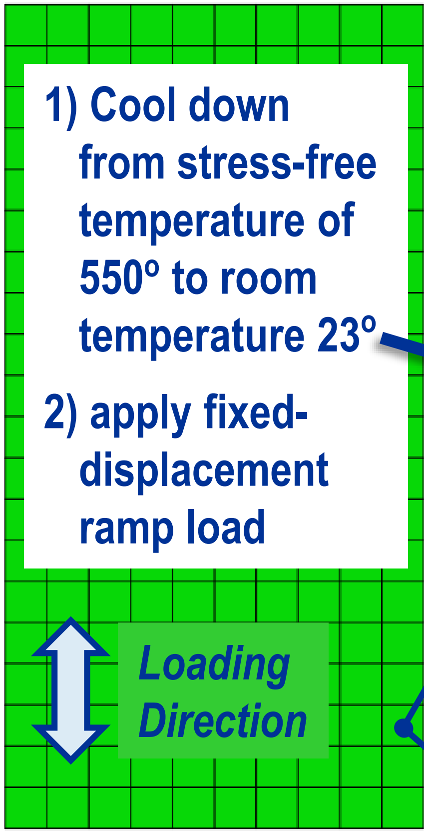
SiC/RBSN

Bhatt & Phillips (1990)



SiC/RBSN Example Procedure & Setup

Abaqus FEA
S4 Shell elements
Fixed-displacement ramp load



(10x20 mesh)

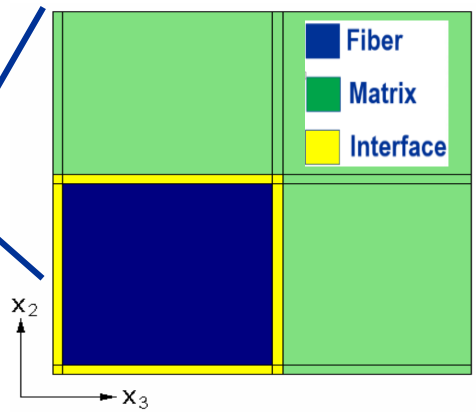
Stochastic strength analysis:

(from individual trials / simulations / realizations)

- Use ***CARES Unit Sphere*** failure criterion
  - ***assume Isotropic material constituent strength – for simplicity and initial testing***

Residual stresses in constituents

MAC/GMC RUC



- **Weibull parameters correlated to experimental results for 0° tensile specimen**
- **Interface strength made large:**
  - *- Encourage matrix to fail before interface*

- ***Interfacial failure modes and sliding resistance not considered***

Constituent properties of SiC/RBSN with anisotropic thermal expansion coefficients

Constituent	Modulus, GPa	Poisson ratio	Longitudinal coefficient of thermal expansion, α_L (m/m/°C)	Transverse coefficient of thermal expansion, α_T (m/m/°C)
Fiber	390	0.17	$\boxed{4.1\times10^{-6}}$	$\boxed{1.84\times10^{-6}}$
Matrix	110	0.22	2.2×10^{-6}	2.2×10^{-6}
Interface	1.8	0.22	2.0×10^{-6}	2.0×10^{-6}

Assumed Weibull Parameters:

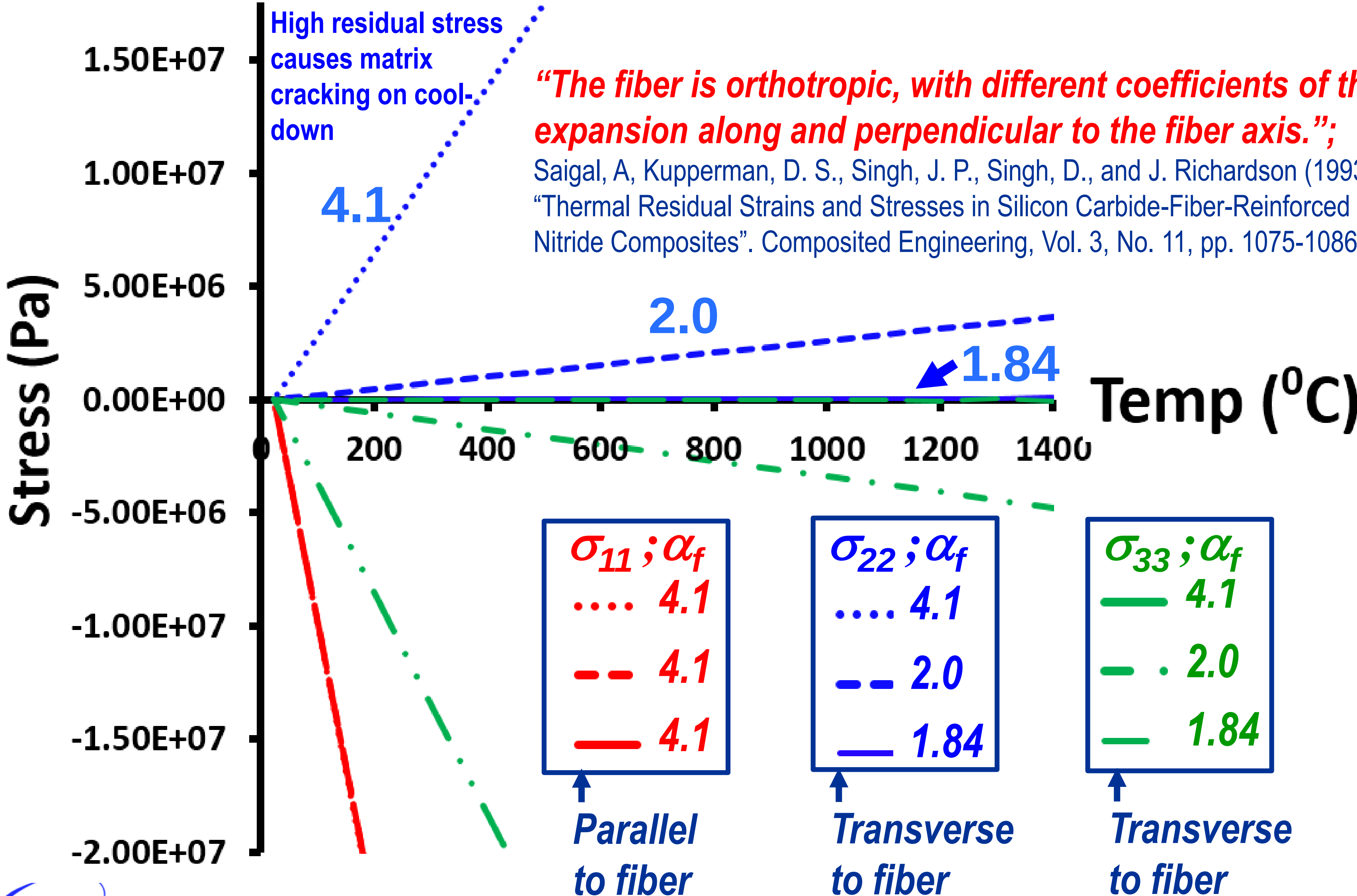
Fiber $m_V = 20$ $\sigma_{oV} = 2875$ Mpa • $m^{3/20}$

Matrix $m_V = 5.0$ $\sigma_{oV} = 150$ Mpa • $m^{3/5}$

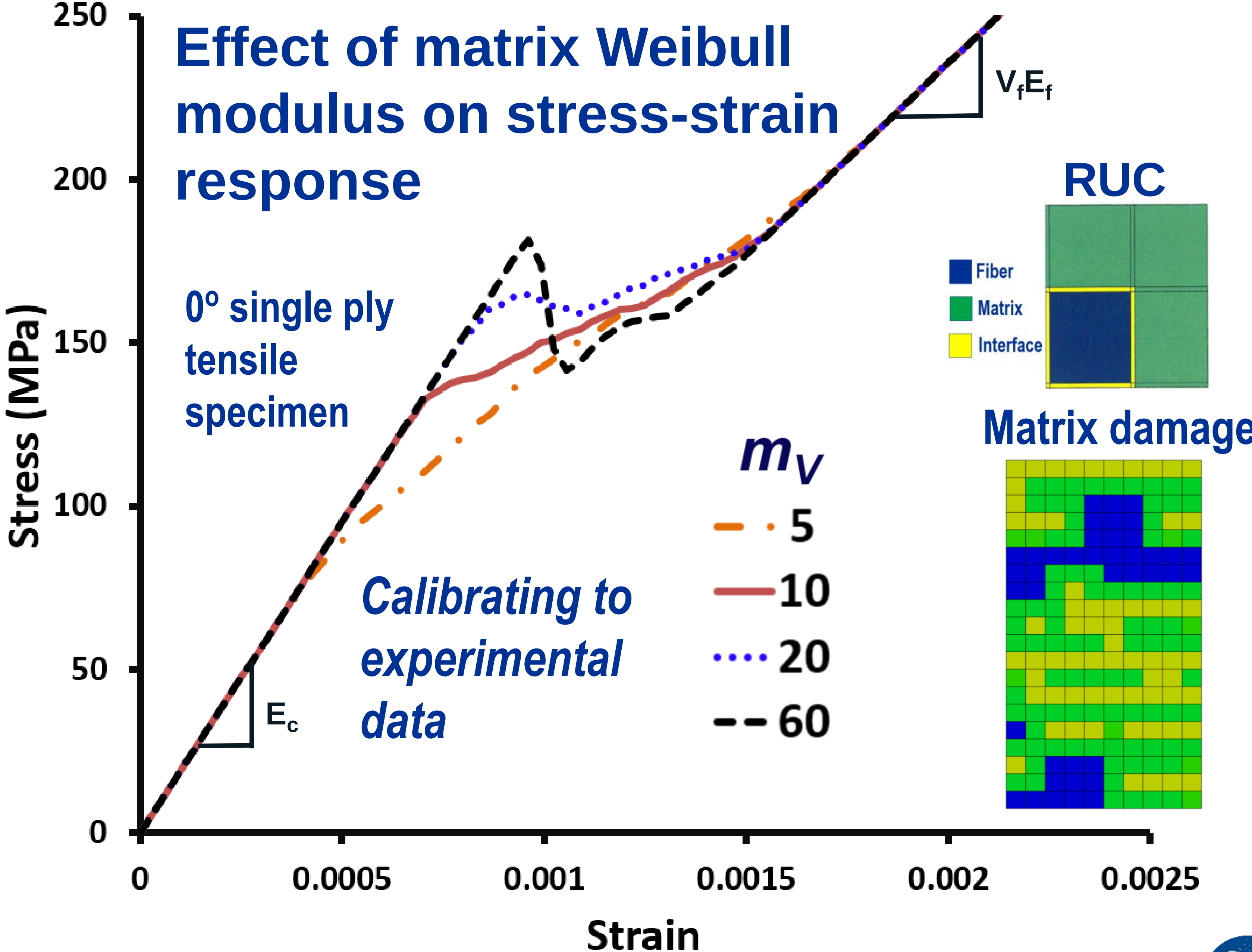
Interface $m_V = 5.0$ $\sigma_{oV} = 80$ Mpa • $m^{3/5}$

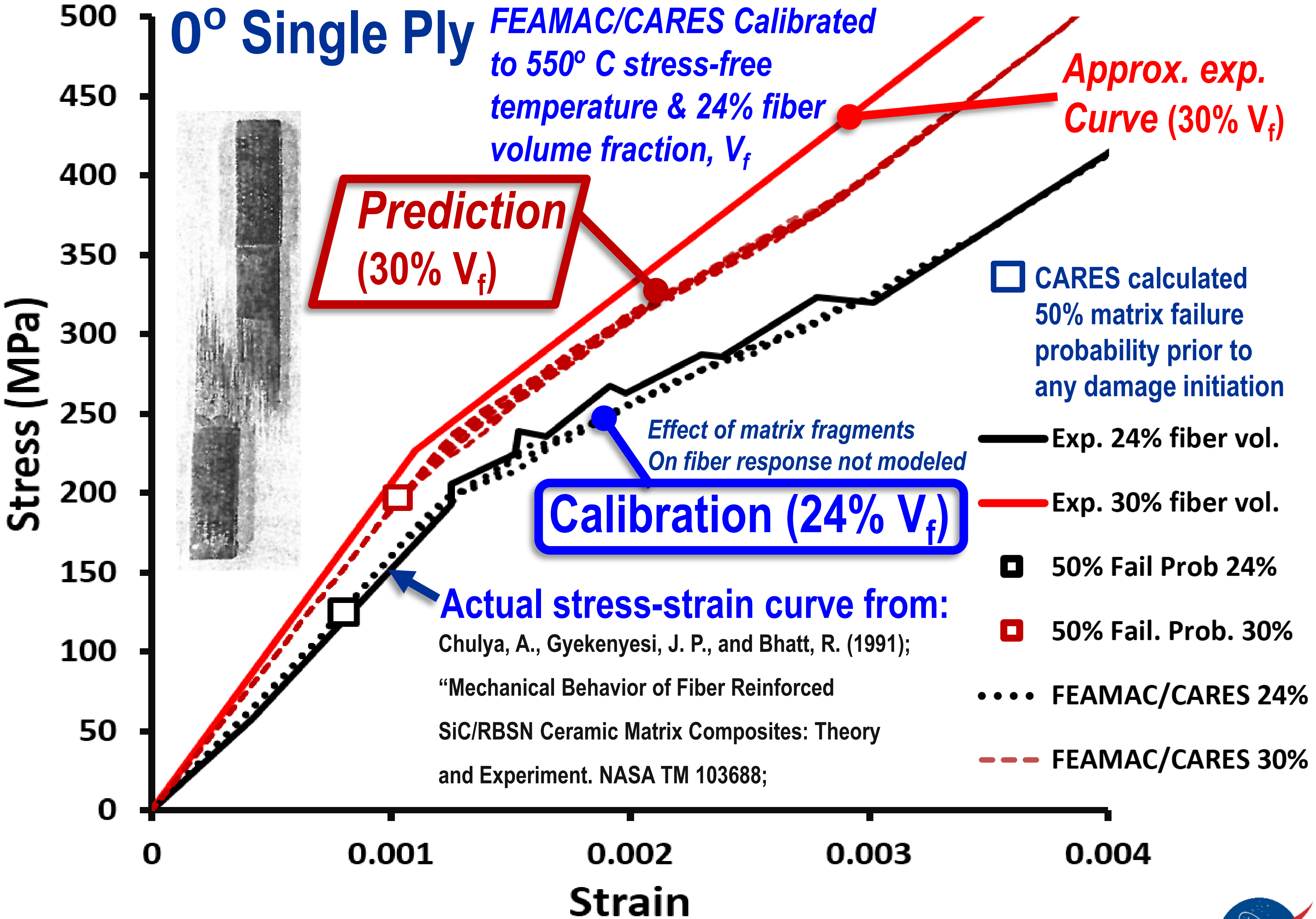
Residual matrix stresses after cool-down from temperature

- **Effect of anisotropic fiber-thermal-expansion-coefficient, α_f on RUC**



Effect of matrix Weibull modulus on stress-strain response



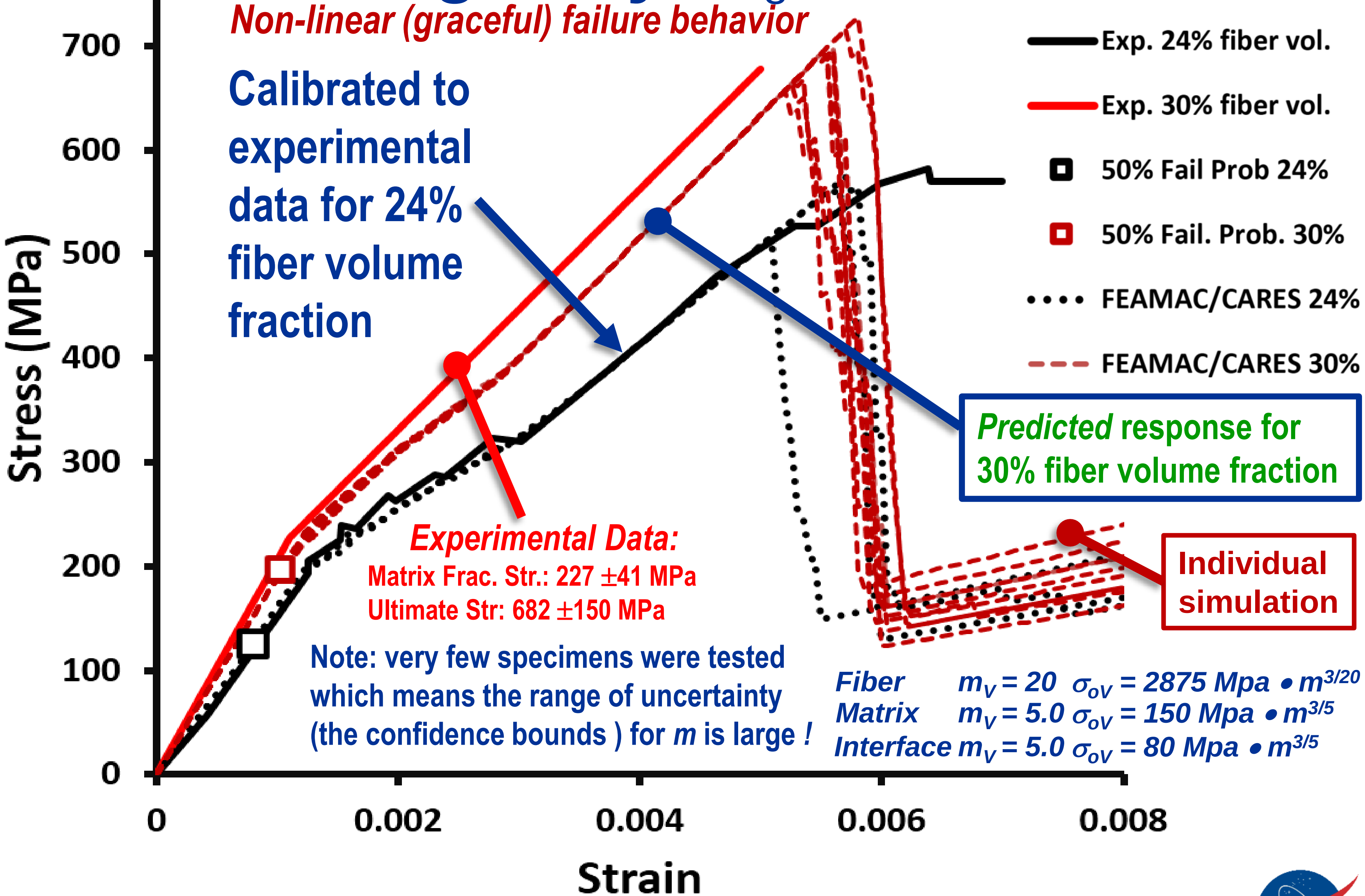


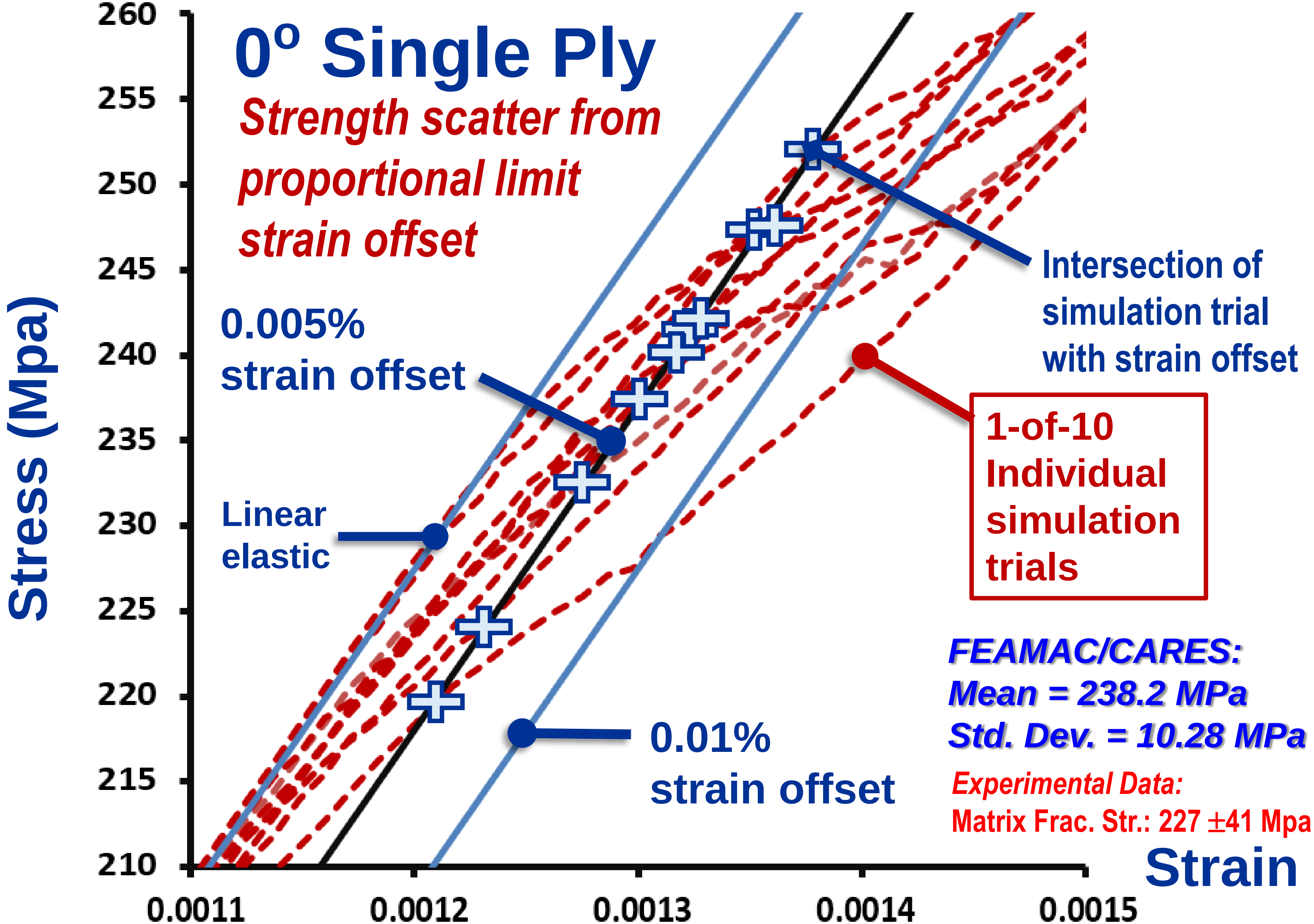
0° Single Ply
FEAMAC/CARES Calibrated to 550° C stress-free temperature & 24% fiber volume fraction, V_f
Approx. exp. Curve (30% V_f)
Prediction (30% V_f)
CARES calculated 50% matrix failure probability prior to any damage initiation
Effect of matrix fragments On fiber response not modeled
Calibration (24% V_f)
Exp. 24% fiber vol.
Exp. 30% fiber vol.
50% Fail Prob 24%
50% Fail. Prob. 30%
FEAMAC/CARES 24%
FEAMAC/CARES 30%
Actual stress-strain curve from:
Chulya, A., Gyekenyesi, J. P., and Bhatt, R. (1991);
"Mechanical Behavior of Fiber Reinforced SiC/RBSN Ceramic Matrix Composites: Theory and Experiment. NASA TM 103688;
Stress (MPa)
Strain
0
50
100
150
200
250
300
350
400
450
500
0
0.001
0.002
0.003
0.004

0º Single Ply $[0]_8$

Non-linear (graceful) failure behavior

FEAMAC/CARES analysis was for a single ply to speed computation

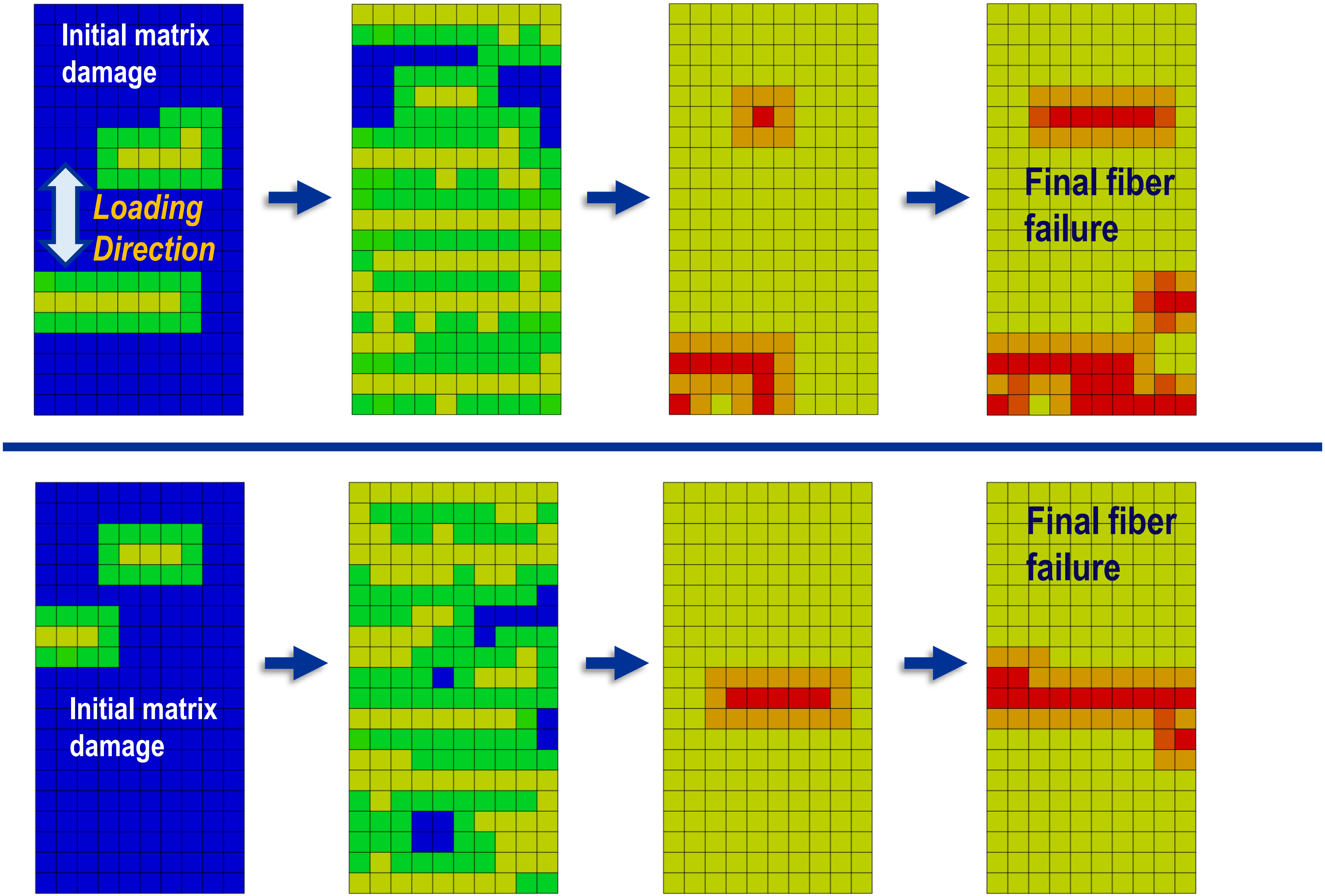




PLS is defined as the stress at 0.005% strain offset:

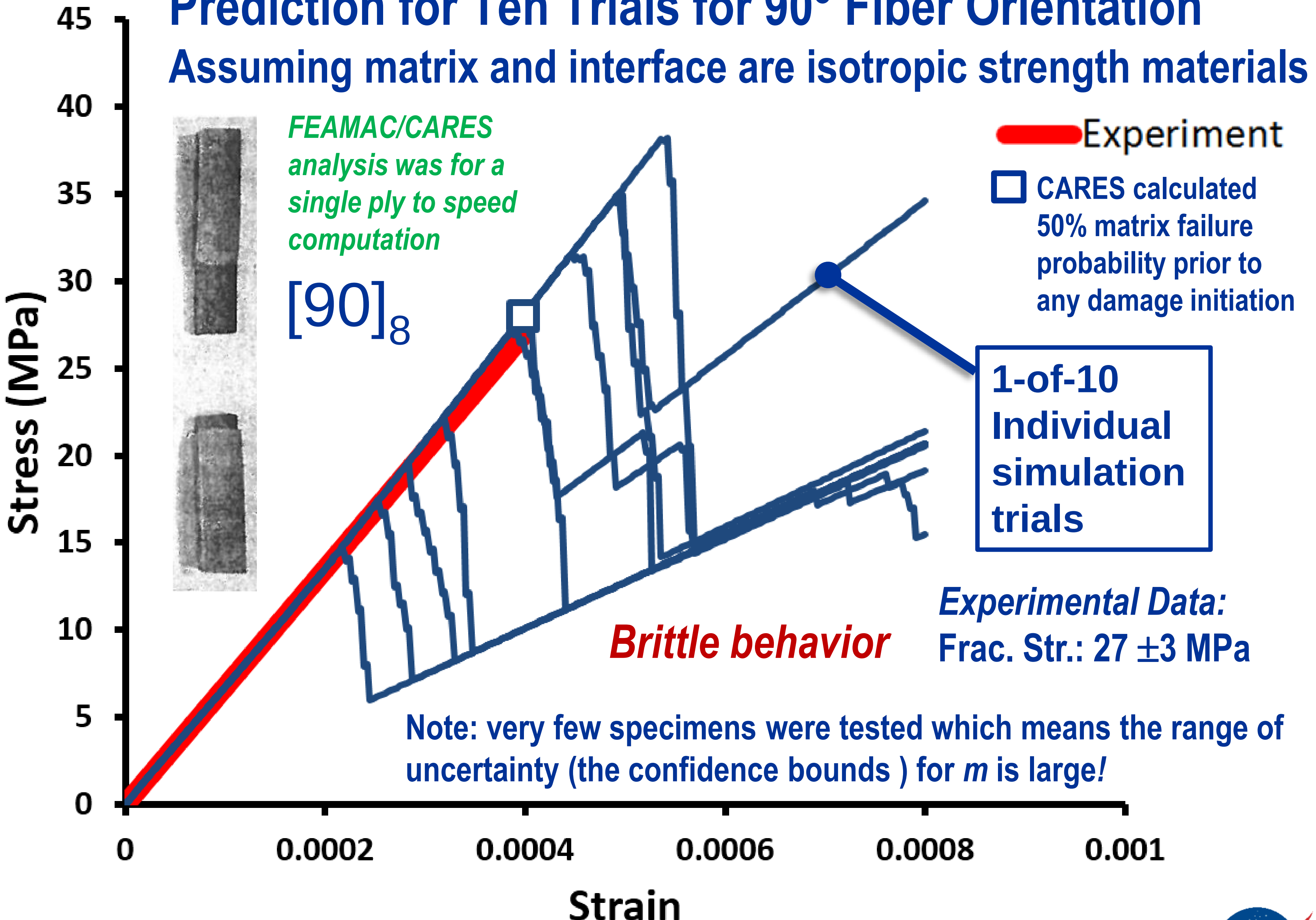
Kalluri, S; Calomino, A; and Brewer, D., " Computation of Variability in the Average Thermal and Mechanical Properties of a Melt-Infiltrated SiC/SiC Composite", High Temperature Ceramic Matrix Composites 5, M. Singh, R.J. Kearns, E. Lara-Curzio, R. Naslain, Eds, 2004, pp. 279-284

Damage progression of 0º tensile specimen - two trials (undeformed plot)

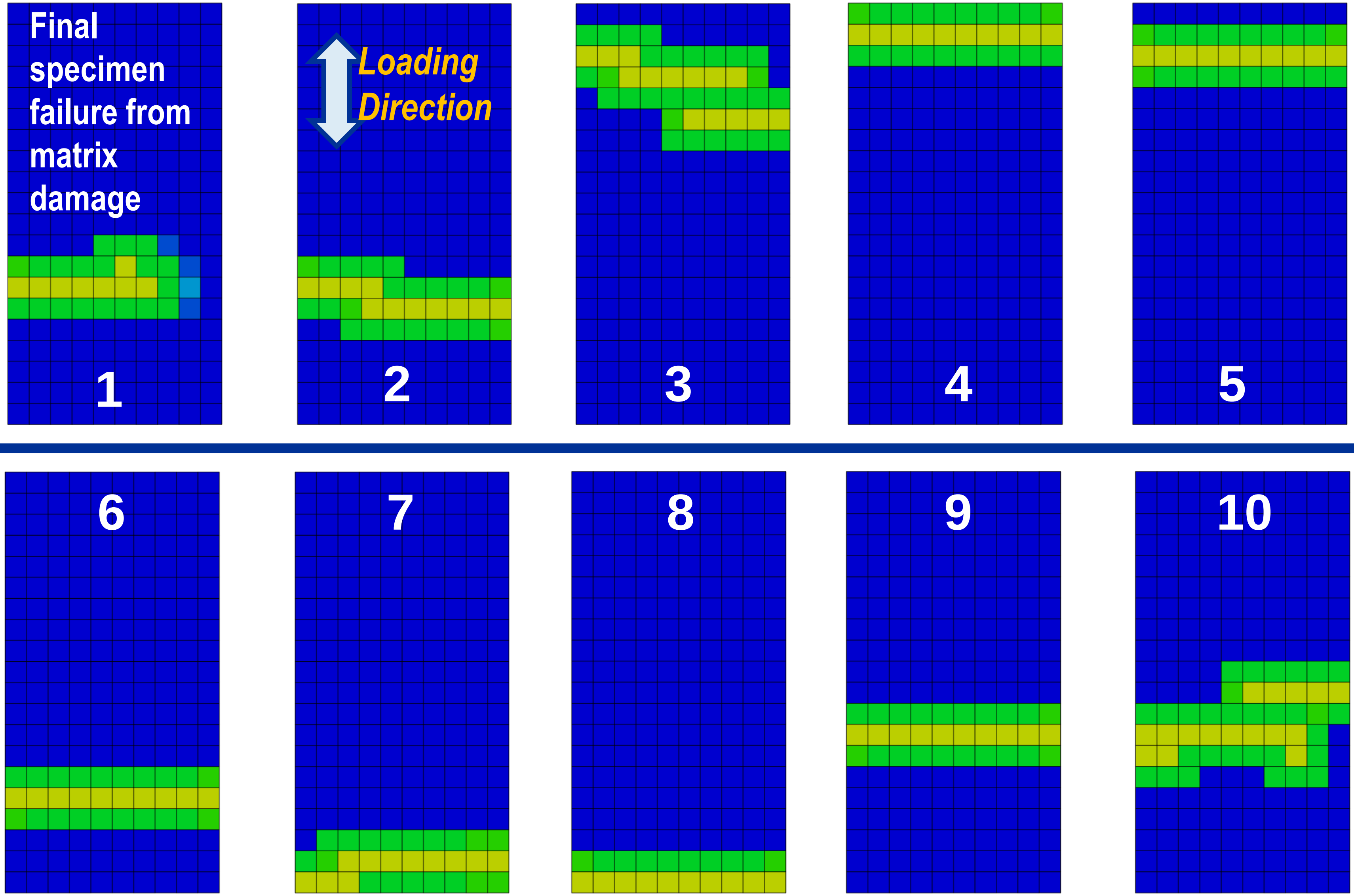


Prediction for Ten Trials for 90° Fiber Orientation

Assuming matrix and interface are isotropic strength materials

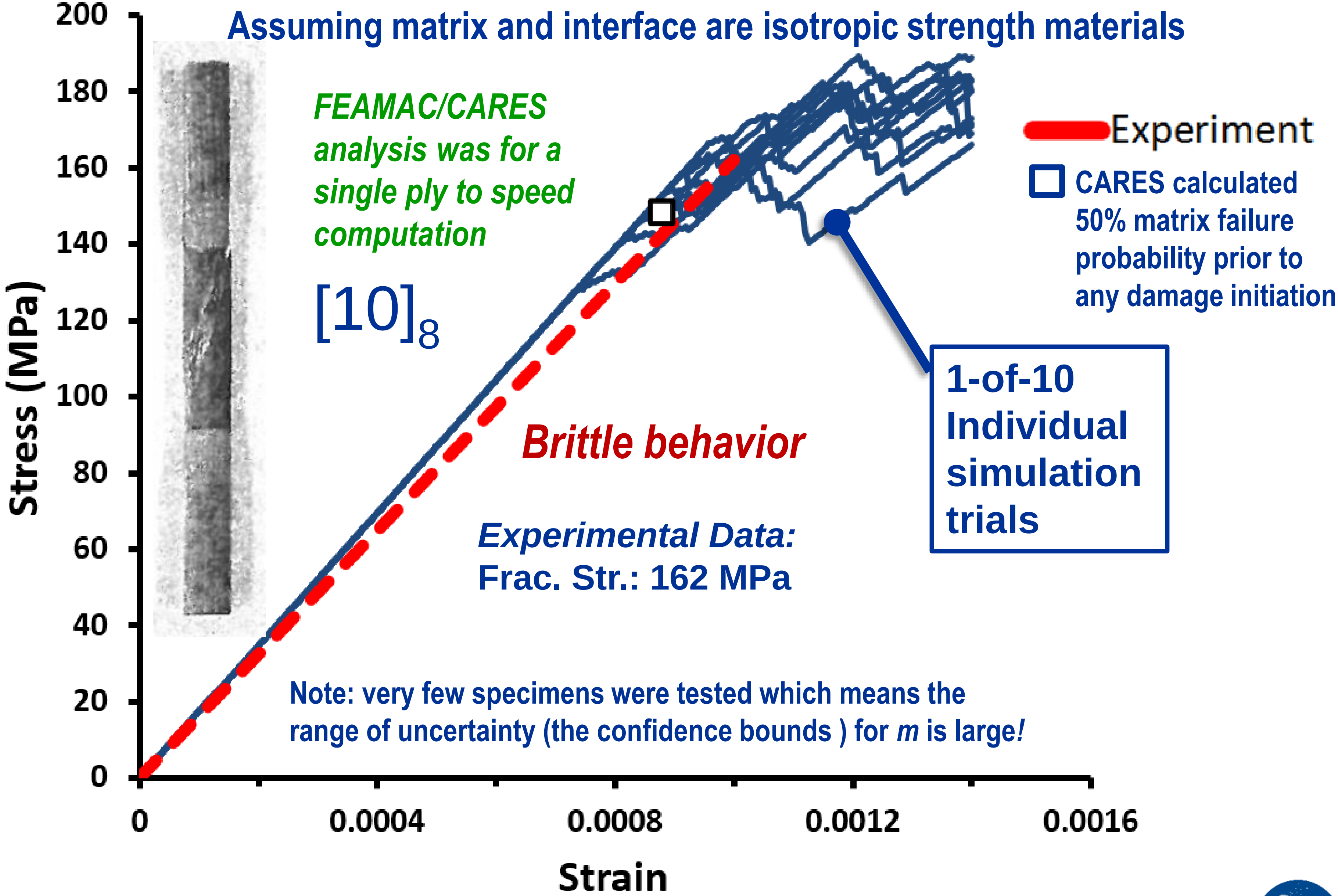


90º Tensile specimen *at final failure for 10 trials* – Undeformed plots



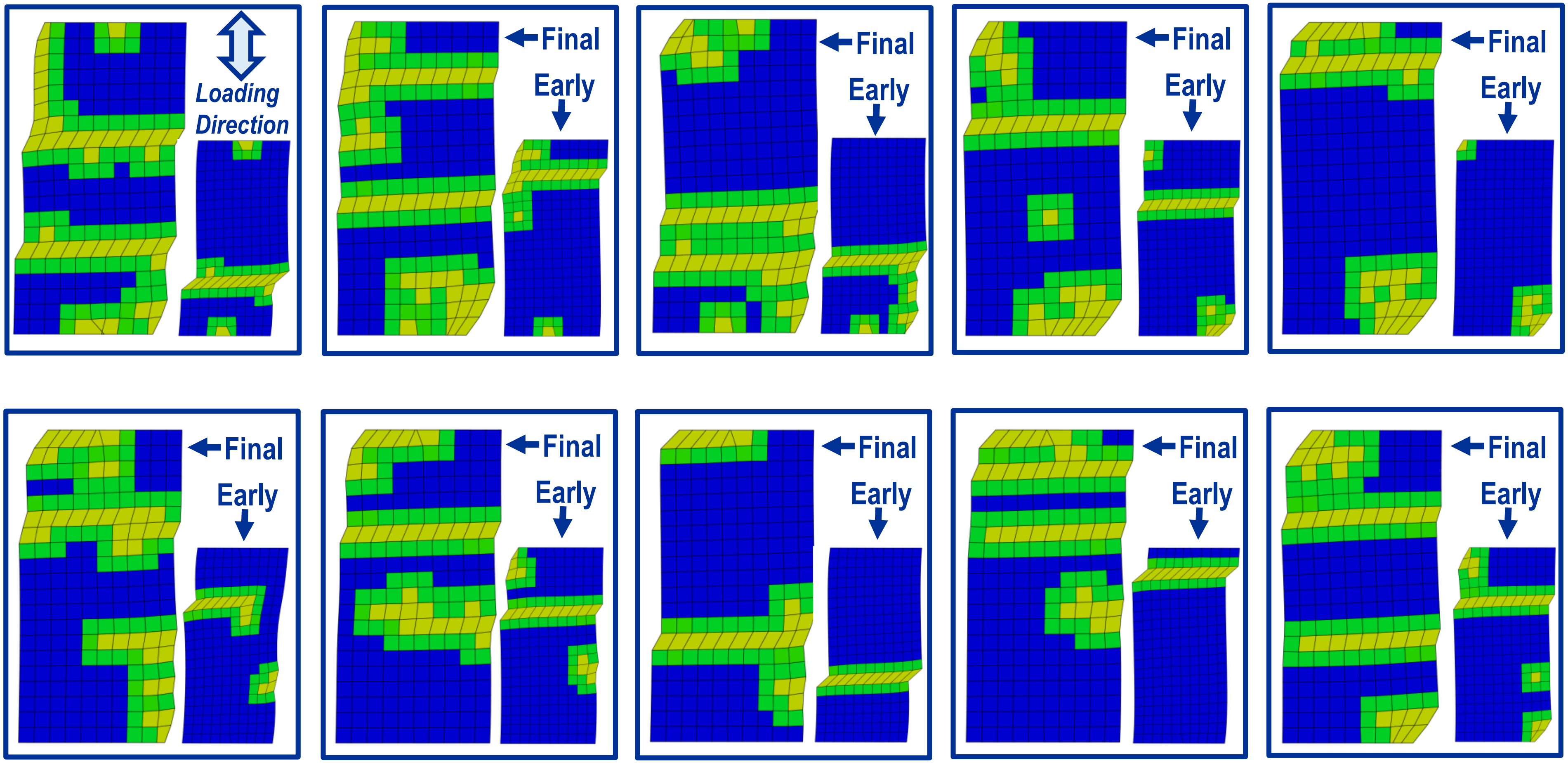
Prediction for Ten Trials for 10° Fiber Orientation

Assuming matrix and interface are isotropic strength materials



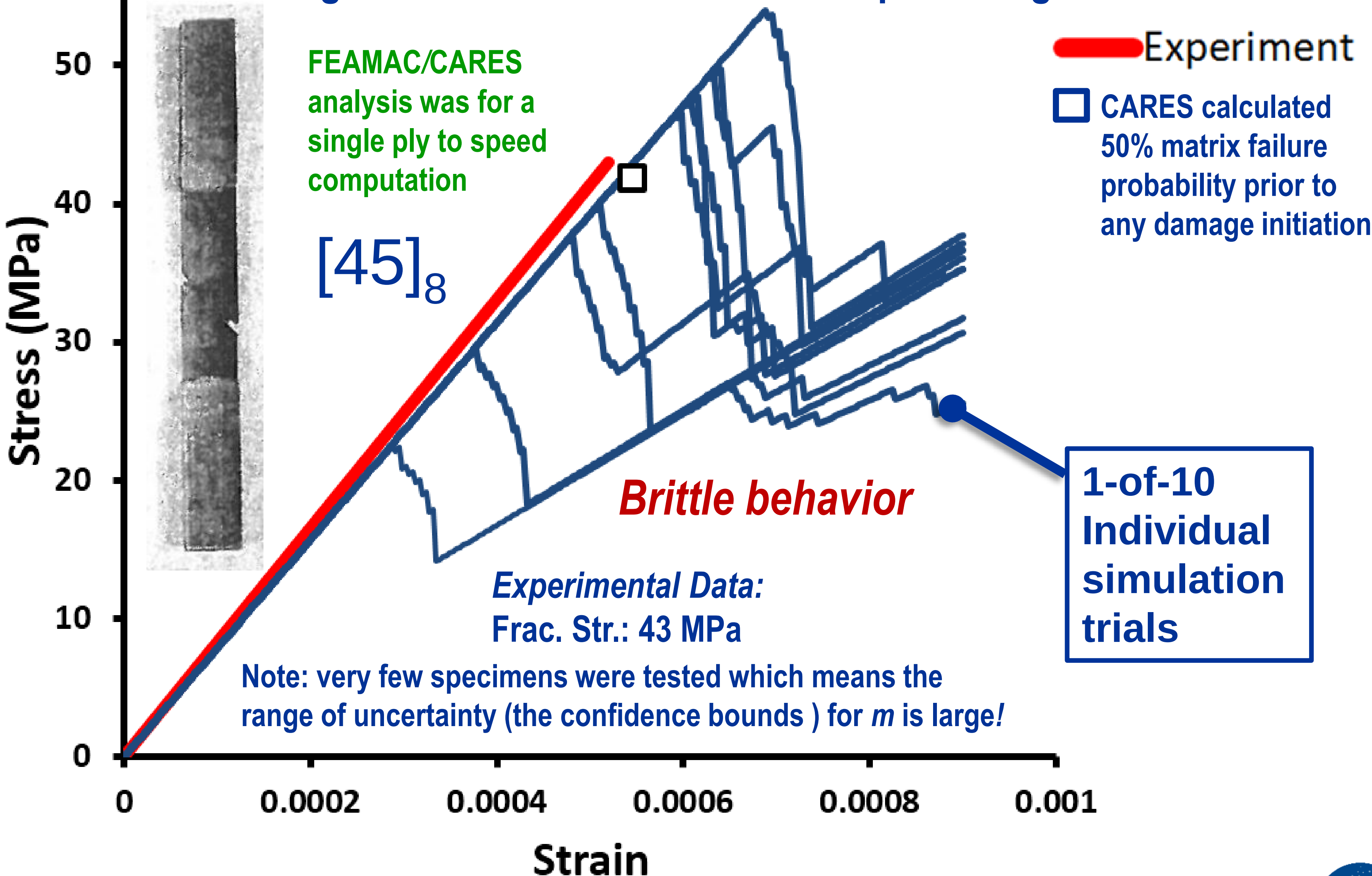
10^0 off-axis tensile specimen; 10 trials at final (matrix) failure; deformed plots

- Edges are allowed to freely deform (warp) on cool-down
- *After cool-down;* bottom edge fixed in loading direction when displacement load applied
- After cool-down; single node along top edge (middle) fixed in direction perpendicular to displacement direct.



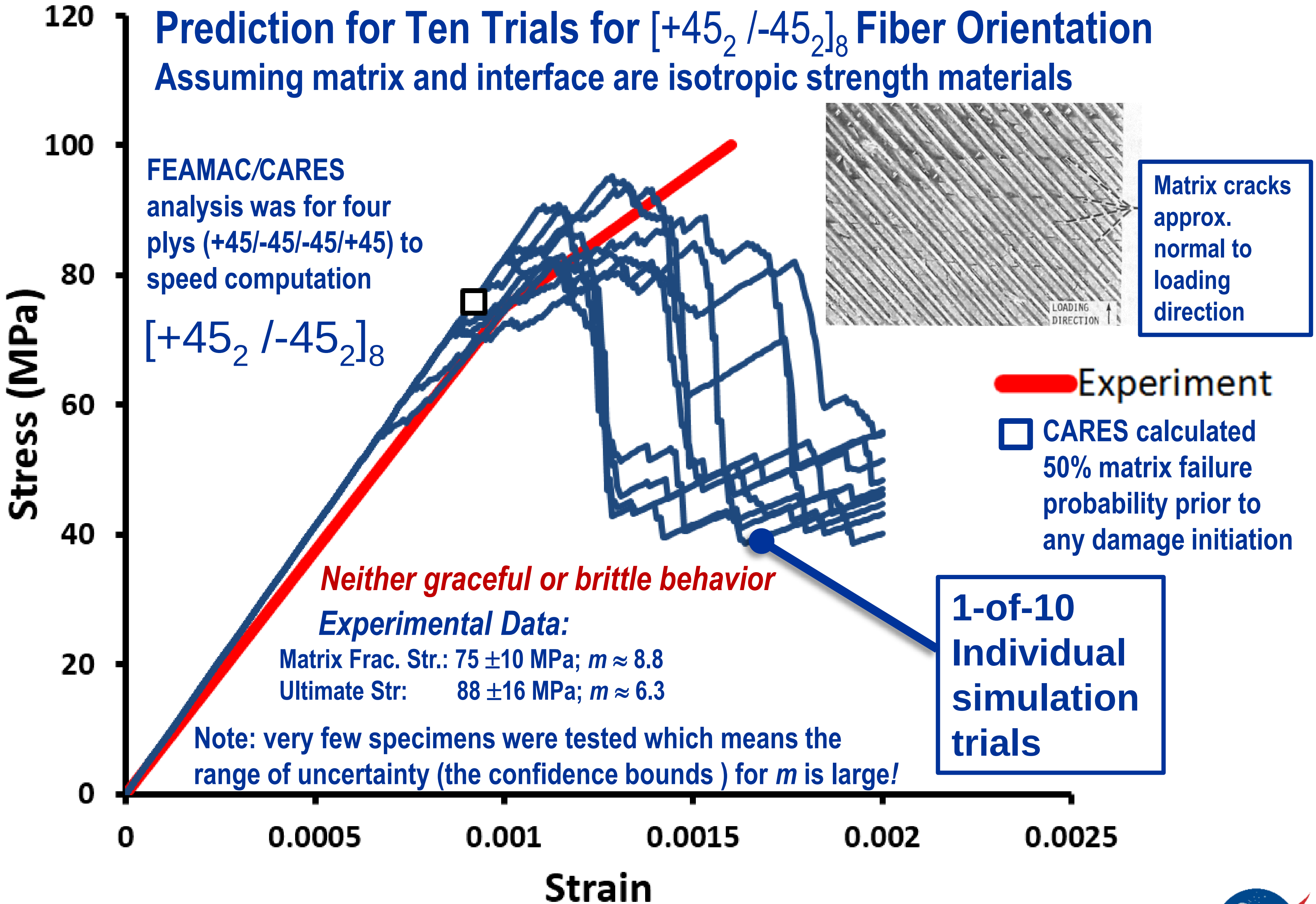
Prediction for Ten Trials for 45° Fiber Orientation

Assuming matrix and interface are isotropic strength materials



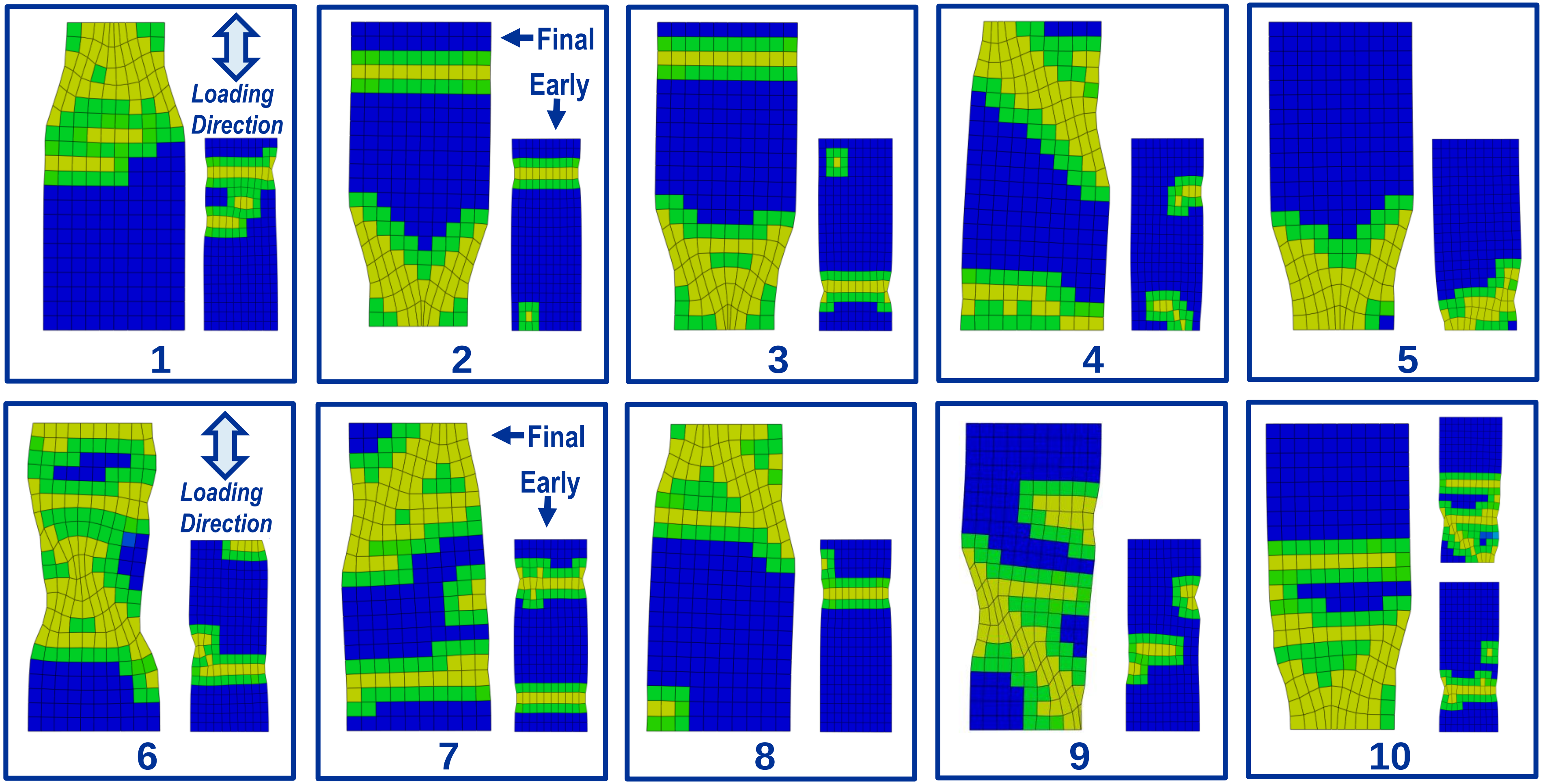
Prediction for Ten Trials for $[+45_2 / -45_2]_8$ Fiber Orientation

Assuming matrix and interface are isotropic strength materials



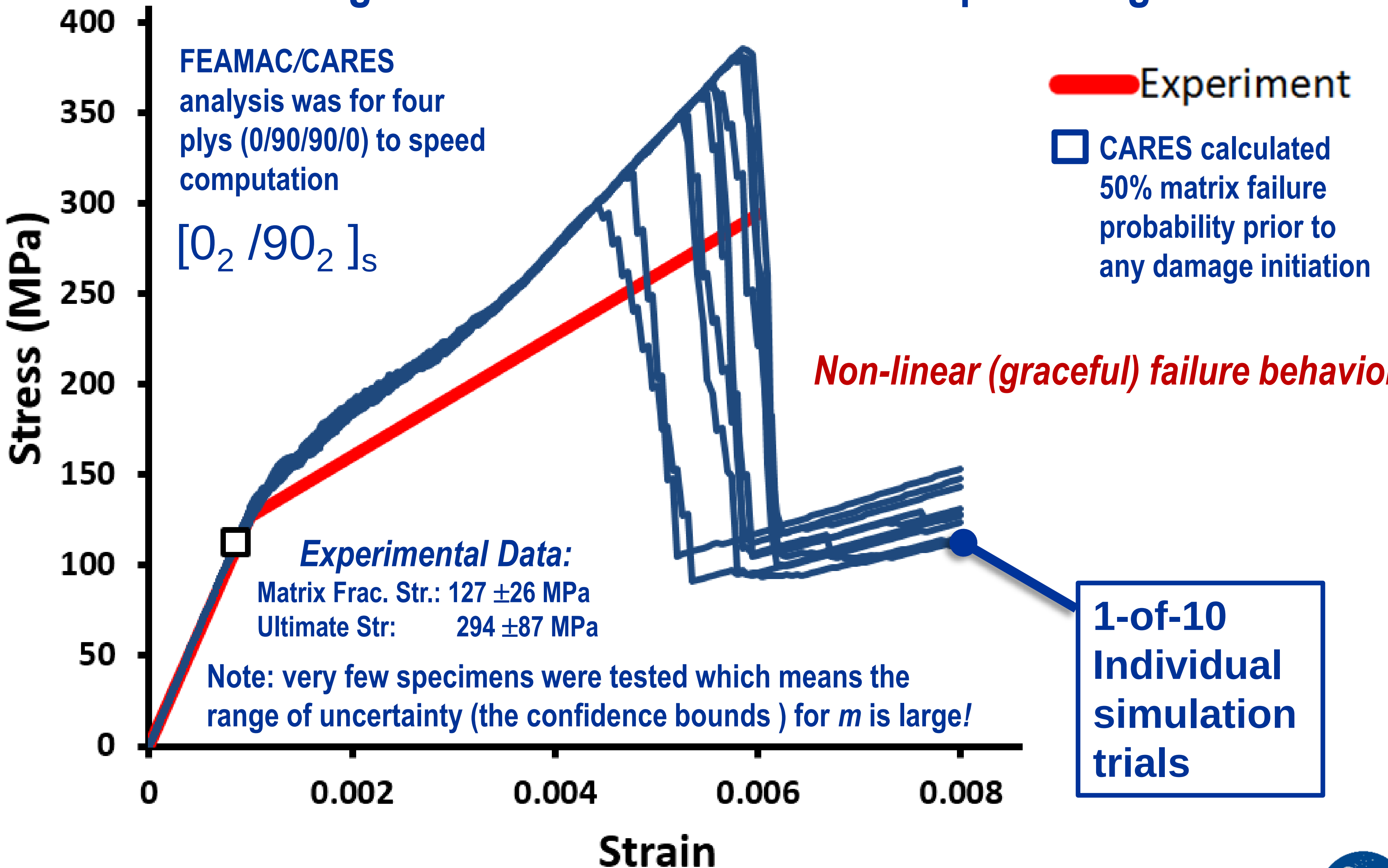
For $[+45_2\ /{-45_2}]_8$ Fiber Orientation; 10 trials at final (matrix) failure; deformed plots

FEAMAC/CARES analysis was for four plys (+45/-45/-45/+45) to speed computation

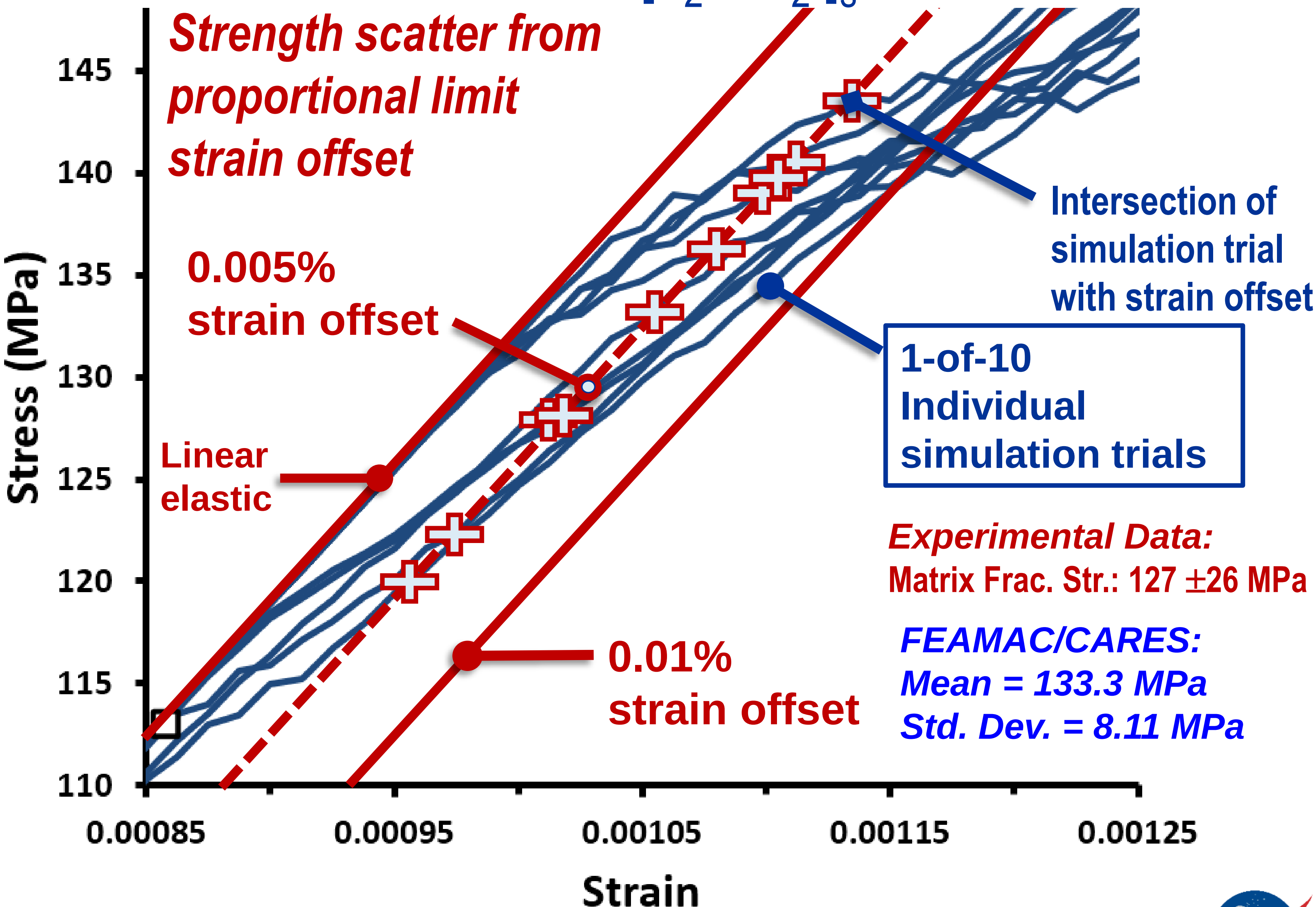


Prediction for Ten Trials for $[0_2/90_2]_s$ Fiber Orientation

Assuming matrix and interface are isotropic strength materials

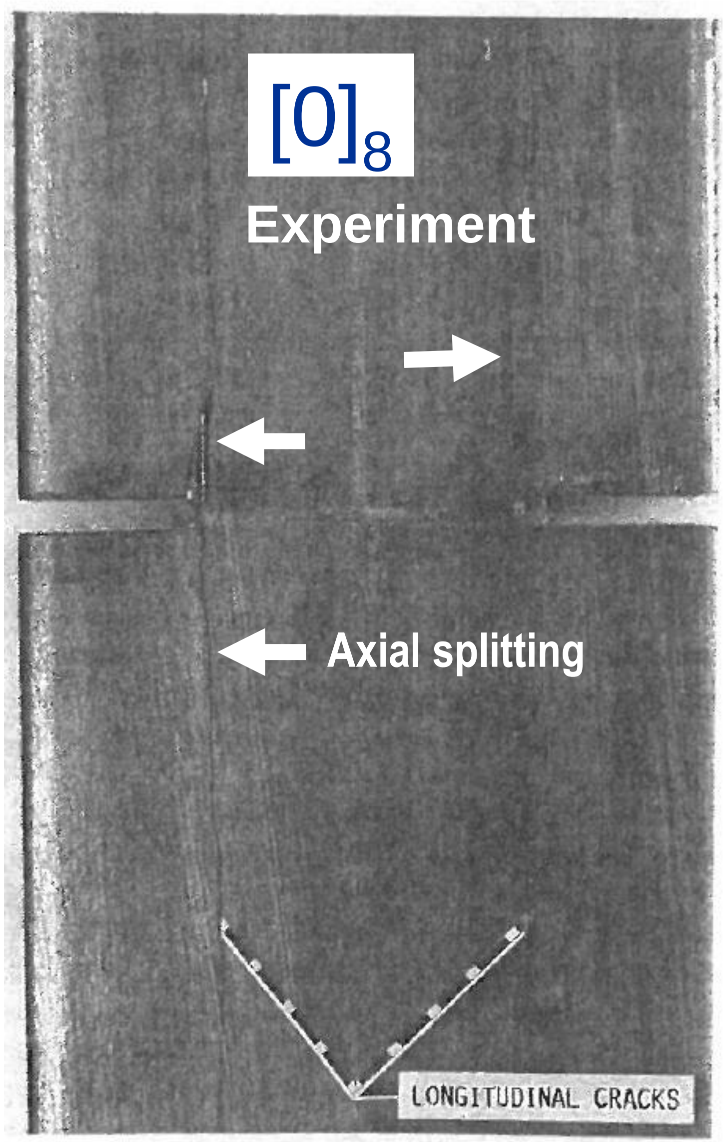


Prediction for Ten Trials for $[0_2/90_2]_s$ Fiber Orientation



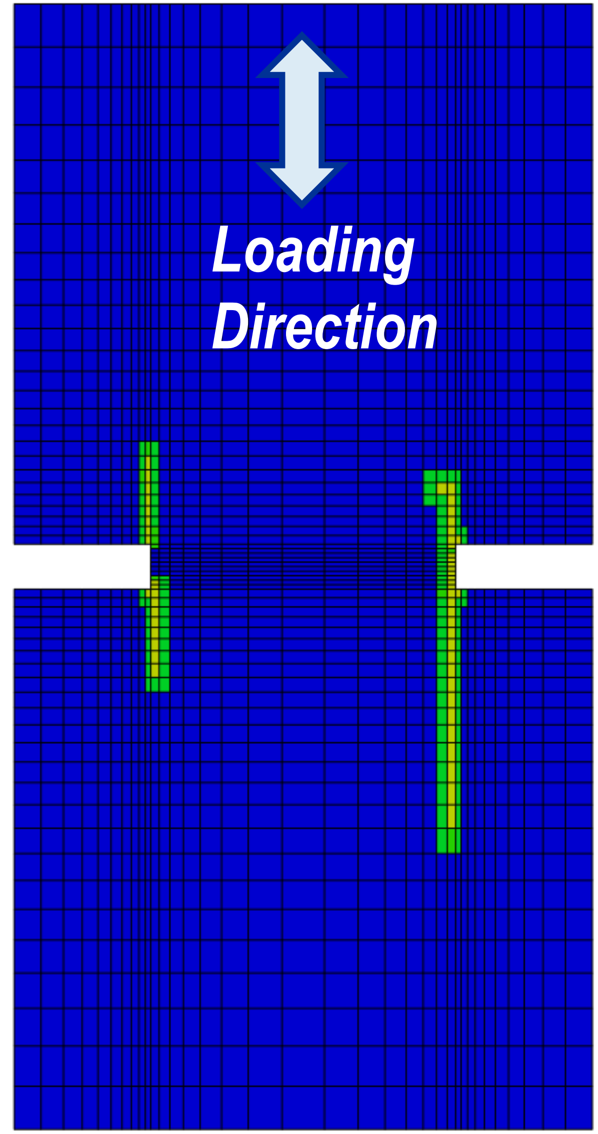
0° Double-Notched Tensile Specimen

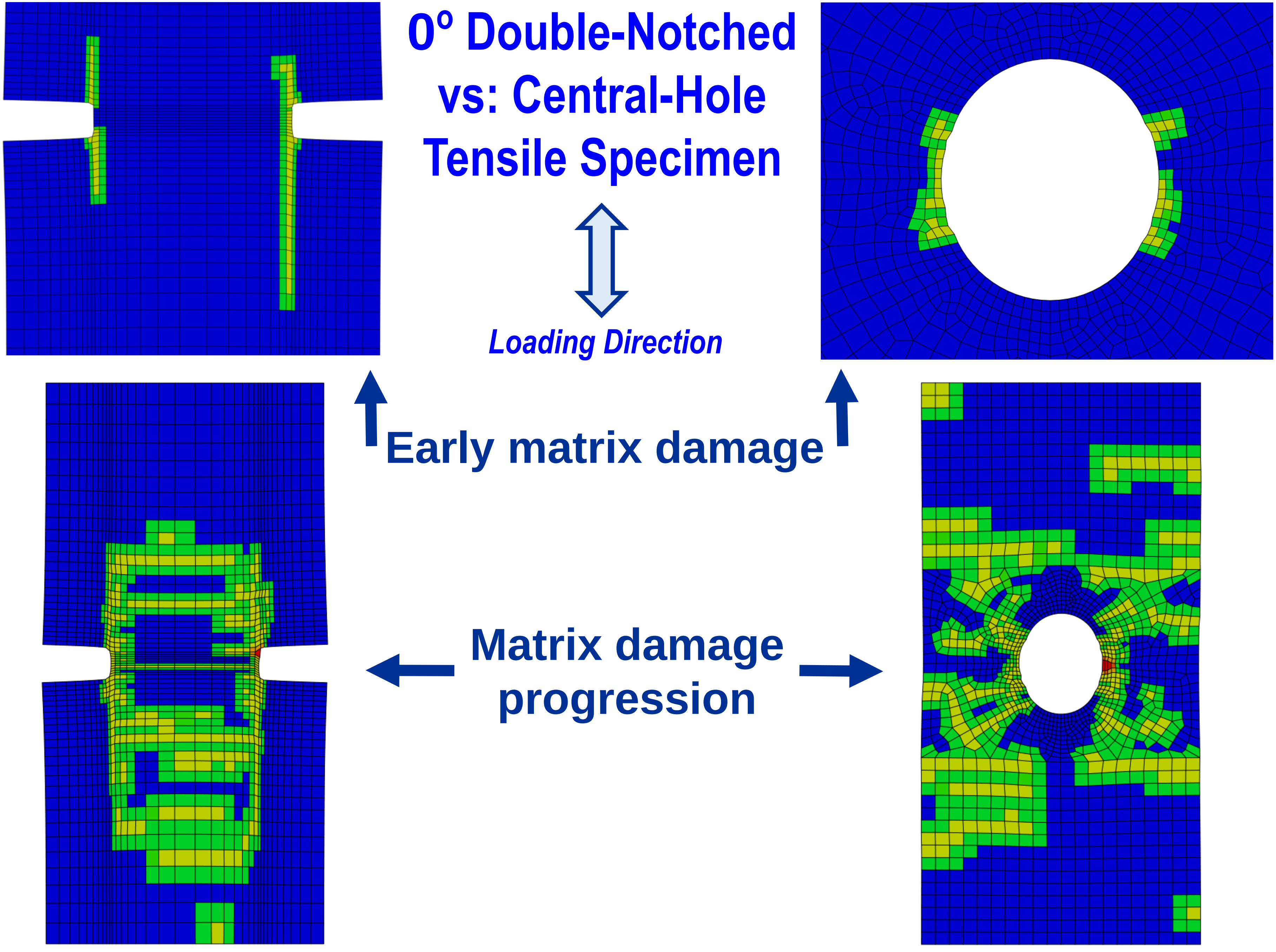
Failure mode showed axial splitting of matrix



Fiber Direction

FEAMAC/CARES analysis was for a single ply to speed computation

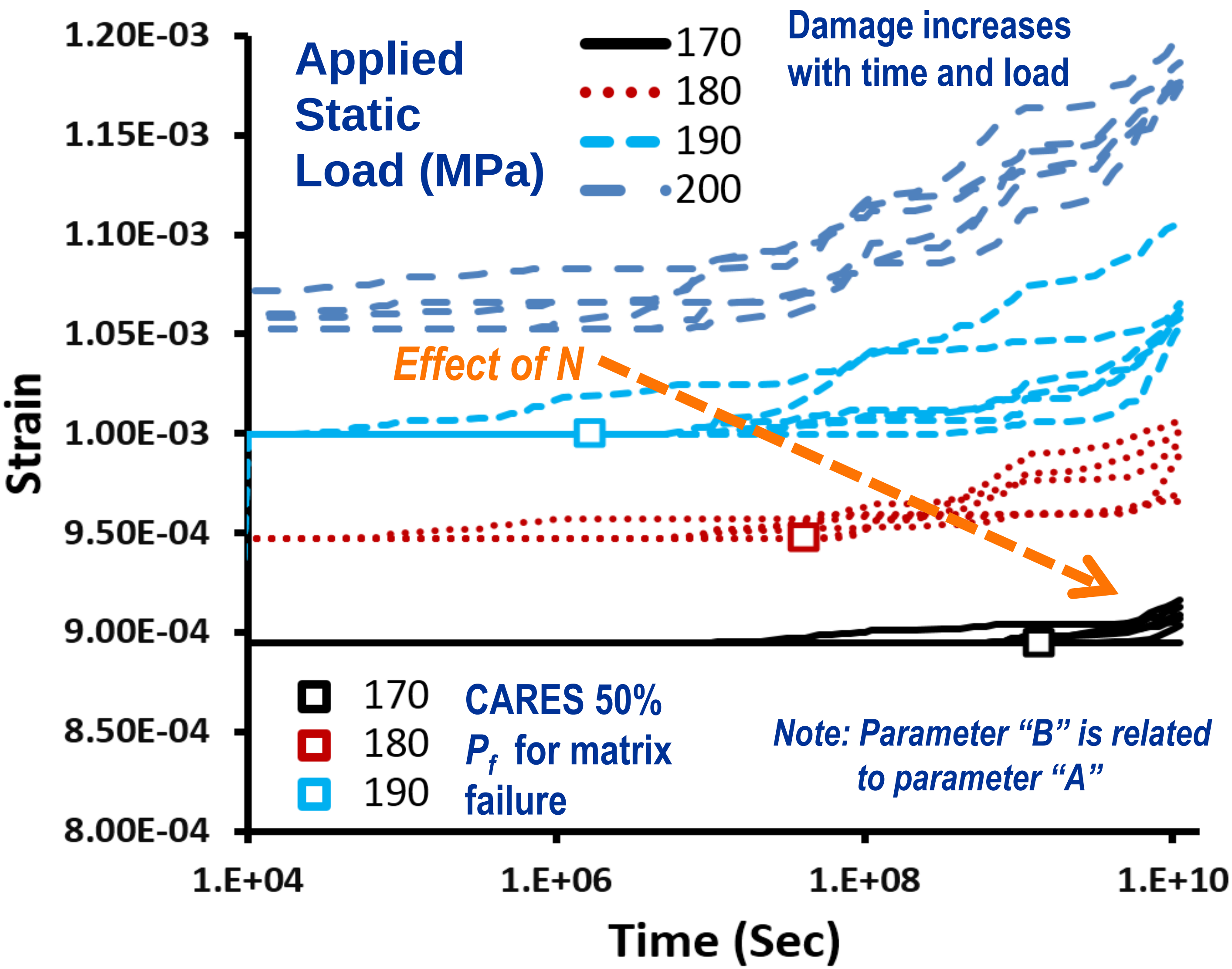



0° Double-Notched
vs: Central-Hole
Tensile Specimen
Loading Direction
Early matrix damage
Matrix damage
progression

Time-dependent Failure Example: Static Loading

(Matrix Damage Accumulation From Slow Crack Growth)

Strain response for applied static tensile load over time



Service life prediction

Longitudinal stress applied to a 0° SiC/RBSN ply

10 time increments per time magnitude

Slow Crack Growth Power Law:

$$\frac{da}{dt} = AK_{Ieq}^{N}$$

Weibull Parameters

m = 7 **(Weibull slope)**

σ_o = 106 Mpa • $mm^{3/7}$

Fatigue Parameters

N = 20 **(fatigue slope)**

B = 1.0E9 MPa^2 • sec

Conclusions

- Progressive damage simulation of composite structures incorporating probabilistic material strength models is possible with the FEAMAC/CARES code
- The Unit Sphere multiaxial model was used predict the strength response of a SiC-RBSN composite for various fiber orientations under uniaxial tension
- Reasonable correlation to matrix cracking strength experimental data was achieved assuming the matrix was an isotropic material with $\boldsymbol{m} \approx 5$, and assuming residual stresses from thermal processing were present
- Brittle behavior vs: non-brittle failure *(graceful failure)* demonstrated
- Localized damage modes at stress concentration features shown

Acknowledgement

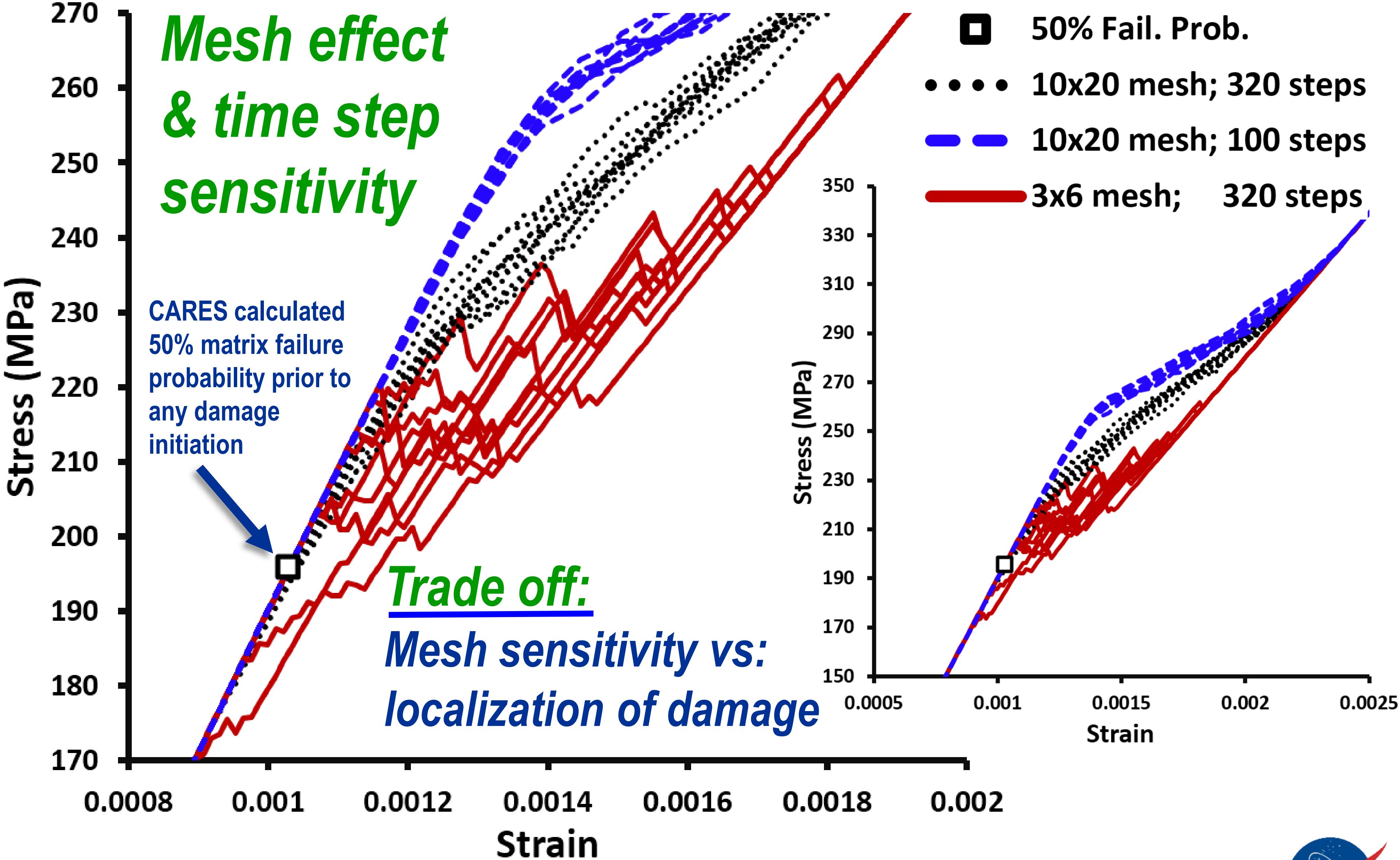
This work was funded by the NASA Transformative Tools and Technologies Program

Extra Material

Abstract:

Reported here is a coupling of two NASA developed codes: CARES (Ceramics Analysis and Reliability Evaluation of Structures) with the MAC/GMC (Micromechanics Analysis Code/ Generalized Method of Cells) composite material analysis code. The resulting code is called FEAMAC/CARES and is constructed as an Abaqus finite element analysis UMAT (user defined material). Here we describe the FEAMAC/CARES code and an example problem (taken from the open literature) of a laminated CMC in off-axis loading is shown. FEAMAC/CARES performs stochastic-strength-based damage simulation response of a CMC under multiaxial loading using elastic stiffness reduction of the failed elements.

0º single ply tensile specimen *(Load parallel to fiber axis)*



Time-Dependent Life Prediction Theory - Slow Crack Growth and Cyclic Fatigue Crack Growth Laws

Power Law: - Slow Crack Growth (SCG)

$$\frac{da}{dt} = AK_{Ieq}^{N}$$

Combined Power Law & Walker Law: SCG and Cyclic Fatigue

$$\frac{da}{dt} = A_1\, g\, K_{Ieq}^{N} + A_2\, f_c (1 - R)^{Q}\, K_{Ieq}^{N}$$

Time-Dependent Life Prediction Theory -
Slow Crack Growth and Cyclic Fatigue Crack Growth Laws with discrete time steps

Modeling individual time steps in the life prediction methodology enables simulating transient events such as turbine start-up/shut-down or atmospheric re-entry. A computationally efficient methodology has been developed that can extrapolate the reliability calculation for an arbitrary number of *Z* cycles – where each cycle is described by *k* number of time steps. This conceivably allows the coupling of other effects such as stiffiness degradation and oxidation effects on the individual time steps and this can be accounted for interactively within the transient finite element and micromechanics analysis.

Transient Life Prediction Theory - Power Law SCG

Reliability formula for *k* discrete time steps over Z cycles:

$$P_{SV}(t_k) = \exp\{-\sum_{i=1}^{n} \frac{V_i}{4\pi}\Big[\int_{\Omega} \Big[\;\ldots\Big[\;\Big[\;\Big(\frac{\sigma_{Ieq,k,T\max}}{\sigma_{0BVk}}\Big)^{N_{V,k}-2} +$$

$$\frac{\sigma_{Ieq,k}^{N_{V,k}}\, Z\Delta t_k}{\sigma_{0BV,k}^{N_{V,k}-2}\, B_{V,k}}\Big]_k^{\frac{m_{V,k}(N_{V,j}-2)}{m_{V,j}(N_{V,k}-2)}} + \frac{\sigma_{Ieq,j}^{N_{V,j}}\, Z\Delta t_j}{\sigma_{0BV,j}^{N_{V,j}-2}\, B_{V,j}}\Big]_j^{\frac{m_{V,j}\;(N_{V,i}-2)}{m_{V,i}(N_{V,j}-2)}} + \ldots.$$

$$\ldots + \frac{\sigma_{Ieq,2}^{N_{V,2}}\, Z\Delta t_2}{\sigma_{0BV,2}^{N_{V,2}-2}\, B_{V,2}}\Big]_2^{\frac{m_{V,2}\;(N_{V,1}-2)}{m_{V,1}(N_{V,2}-2)}} + \frac{\sigma_{Ieq,1}^{N_{V,1}}\, Z\Delta t_1}{\sigma_{0BV,1}^{N_{V1}-2}\, B_{V,1}}\Big]_1^{\frac{m_{V,1}}{N_{V,1}-2}} d\Omega\Big]_i\}$$

Individual time step: Each time step can have different loading, Weibull, and fatigue parameters. Compatibility of failure probability is maintained between the individual time steps

SiC/RBSN Notional Example for SCG

0^o Degree tensile specimen under a static load over time

- Use same 10x20 mesh, RUC, and material properties as previous SiC/RBSN off-axis loading example

Weibull and Slow Crack Growth (SCG) Parameters

Constituent	Weibull modulus, m_V	Weibull scale parameter, σ_{oV}, $\text{MPa} \bullet \text{mm}^{3/m_V}$	Fatigue exponent, N_V (Equation (11))	Fatigue constant, B_V, $\text{MPa}^2 \bullet \text{sec}$ (Equation (17))
Fiber	20.0	2875.0	100.0	1.0×10^{10}
Matrix	7.0	106.0	20.0	1.0×10^{9}
Interface	7.0	60.0	100.0	1.0×10^{10}

Unit Sphere Multiaxial (Batdorf) Model:

Puts linear elastic fracture mechanics into Weibull weakest-link theory

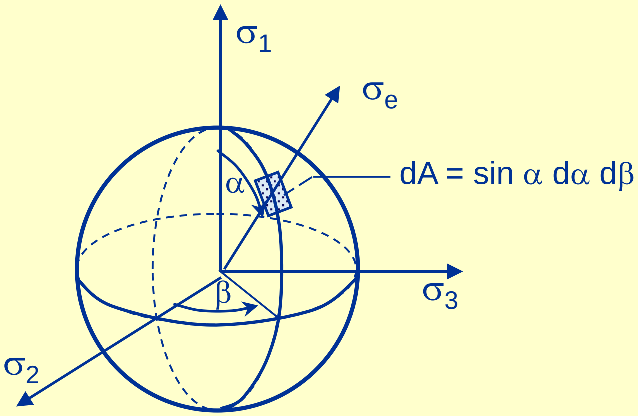
- **Incremental failure probability is the product of two probabilities:**

$$\Delta P_f = P_1 \cdot P_2$$

$\boldsymbol{P_1}$ = Probability of the existence of a crack having a critical strength between σ_c and $\sigma_c + \Delta\sigma_c$ in the incremental volume $\boldsymbol{\Delta V}$

$\boldsymbol{P_2}$ = Probability a crack having a critical strength of σ_c will be oriented in a direction such that it will fail under the applied multiaxial stress state

$\boldsymbol{P_2}$ involves Integration of an equivalent stress σ_e, where $\sigma_e \geq \sigma_c$, over the surface of a unit radius sphere (all possible flaw orientations) divided by the total surface area of the unit radius sphere



σ_e is a function of an assumed crack shape and multiaxial fracture criterion

- **Component failure probability:**

$$P_f = 1 - \exp\left\{ -\int_V \left[\int_0^{\sigma_e} P_1(\sigma_c)\, P_2(\sigma_c)\, \mathrm{d}\sigma_c \right] \mathrm{d}V \right\}$$

Mixed-Mode Fracture Criteria:

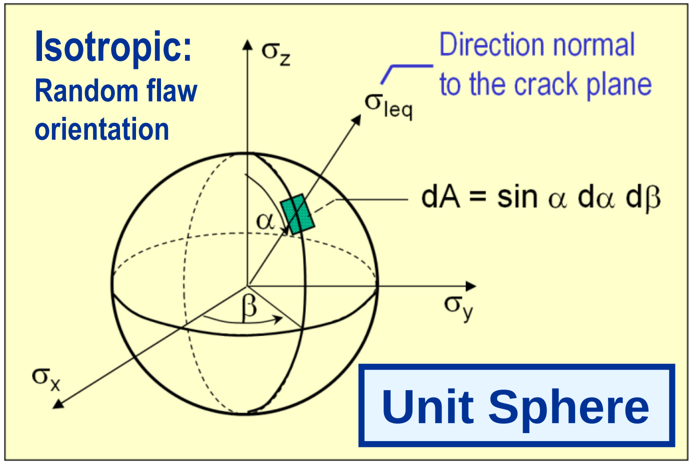
- Normal stress (shear-insensitive cracks)
- Maximum tensile stress
- Total coplanar strain energy release rate
- Noncoplanar (Shetty)

Flaw Shapes:

- Griffith crack
- Penny-shaped crack

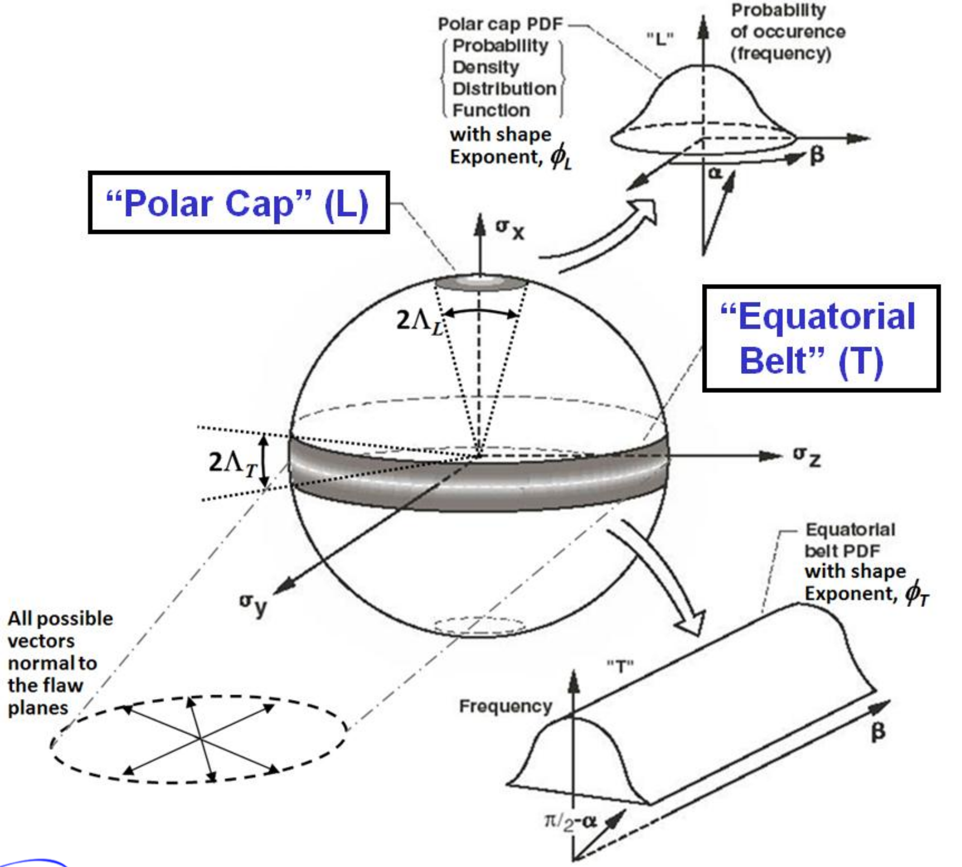
CARES Unit Sphere Multiaxial model

has crack geometry & mixed-mode fracture criterion



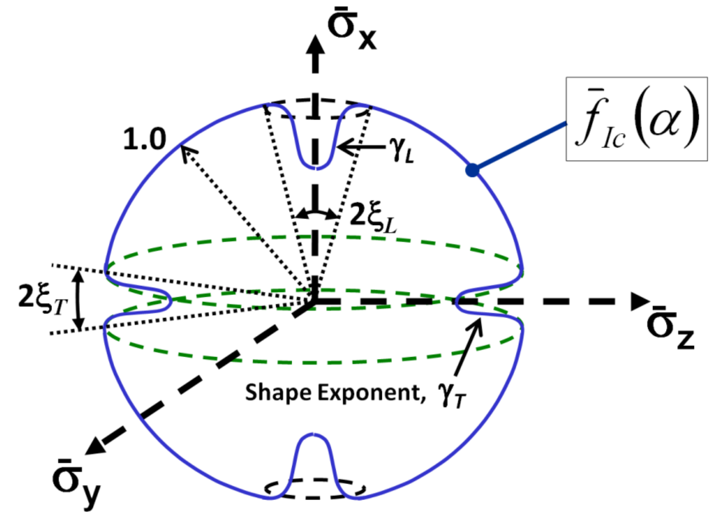
➢ **Two models for transverse isotropy**

(1) Flaw / Fracture-Plane Orientation Anisotropy



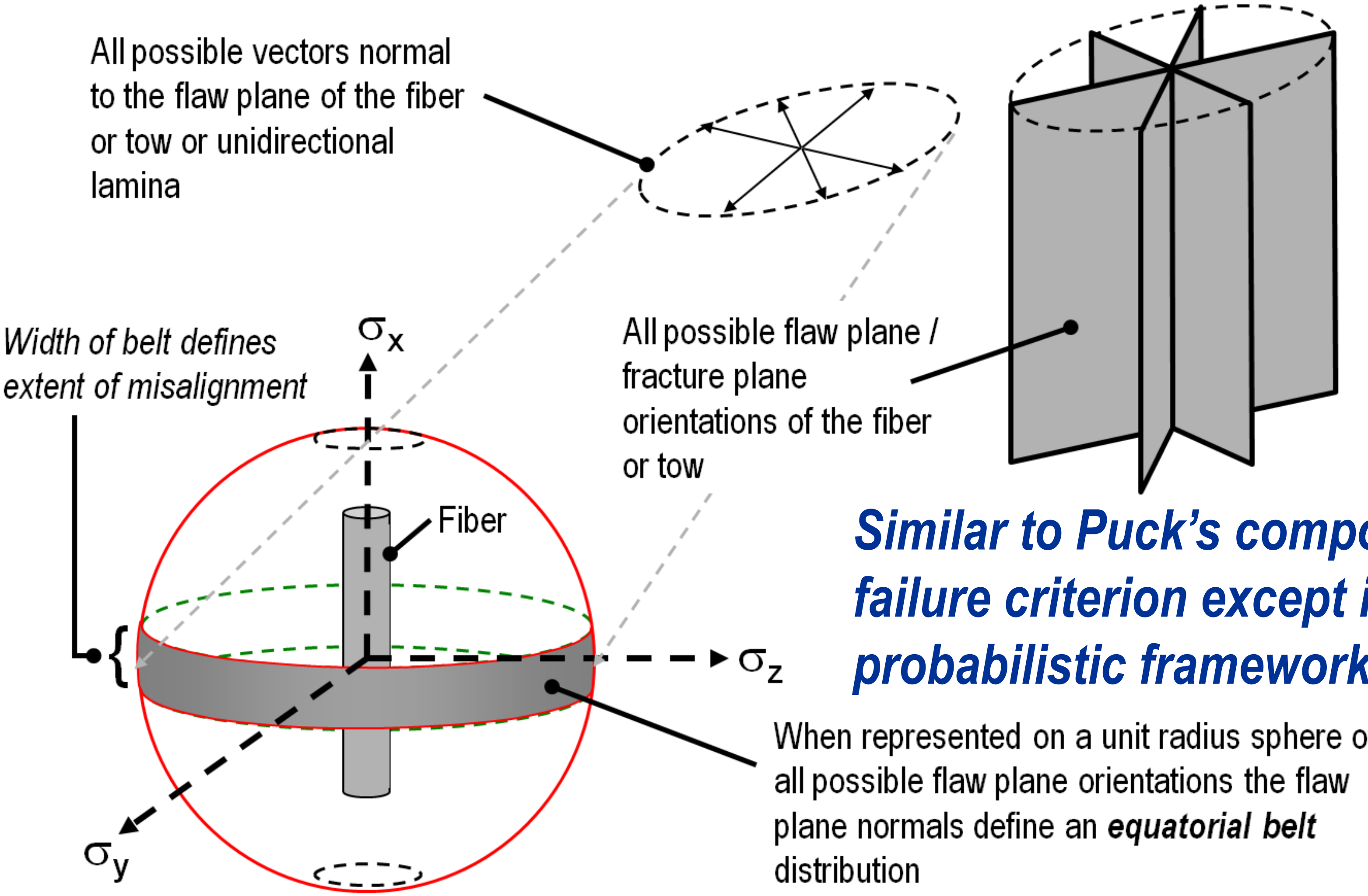
(2) Strength Orientation Anisotropy

σ_{Ic} or K_{Ic} varies with orientation



Nemeth, N.N. (2014): Unit-sphere multiaxial stochastic-strength model applied to a composite material. J. Comp. Mat., Vol. 48(27) Nov. 2014, pp. 3395-3424.

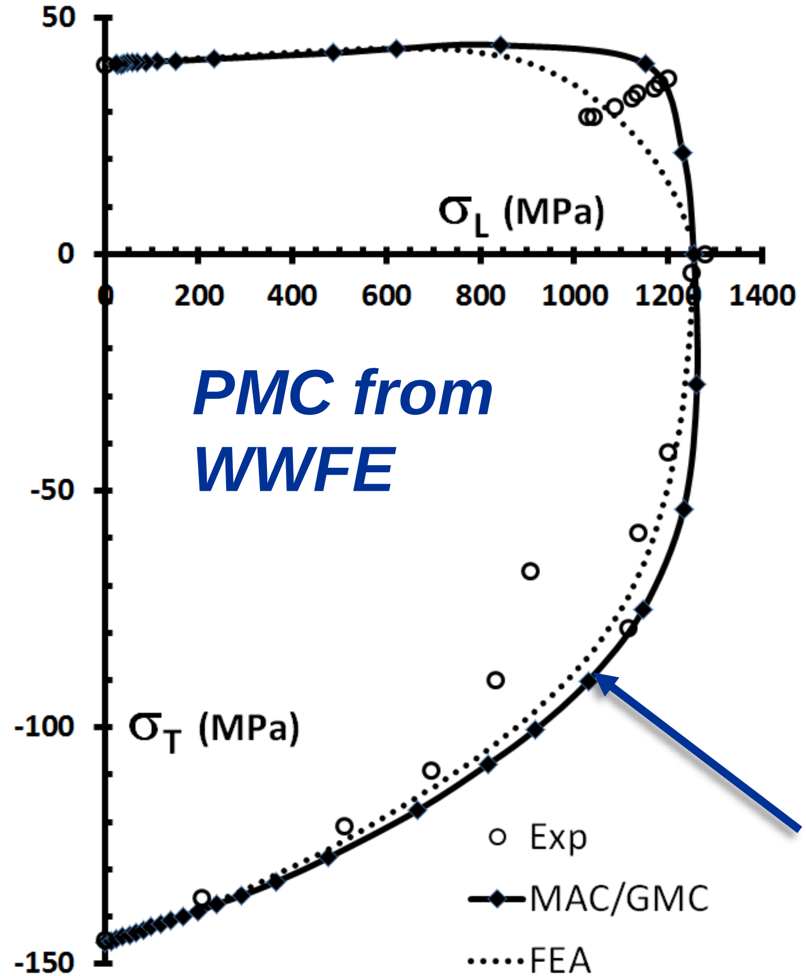
Anisotropic Unit Sphere model defined in a material coordinate system reference frame



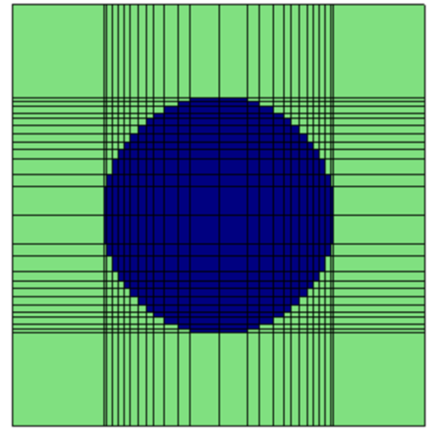
Similar to Puck's composite failure criterion except in a probabilistic framework

Multiaxial Performance: biaxial response predicted from a MAC/GMC RUC for combined longitudinal (L) and transverse (T) loading on a unidirectional PMC vs: FEA.

50% probability of failure envelope.



GMC RUC Used

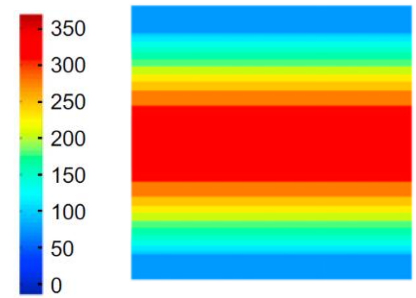


Unit Sphere parameters adjusted so GMC results matched FEA results for uniaxial tension and compression.

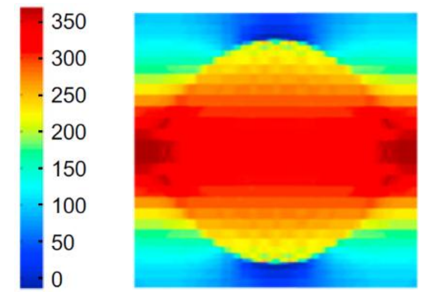
Intermediate points are predictions

Differences in RUC stress fields for a transverse strain:

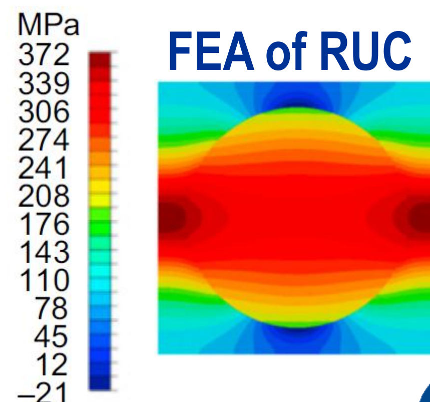
GMC RUC



HF - GMC RUC

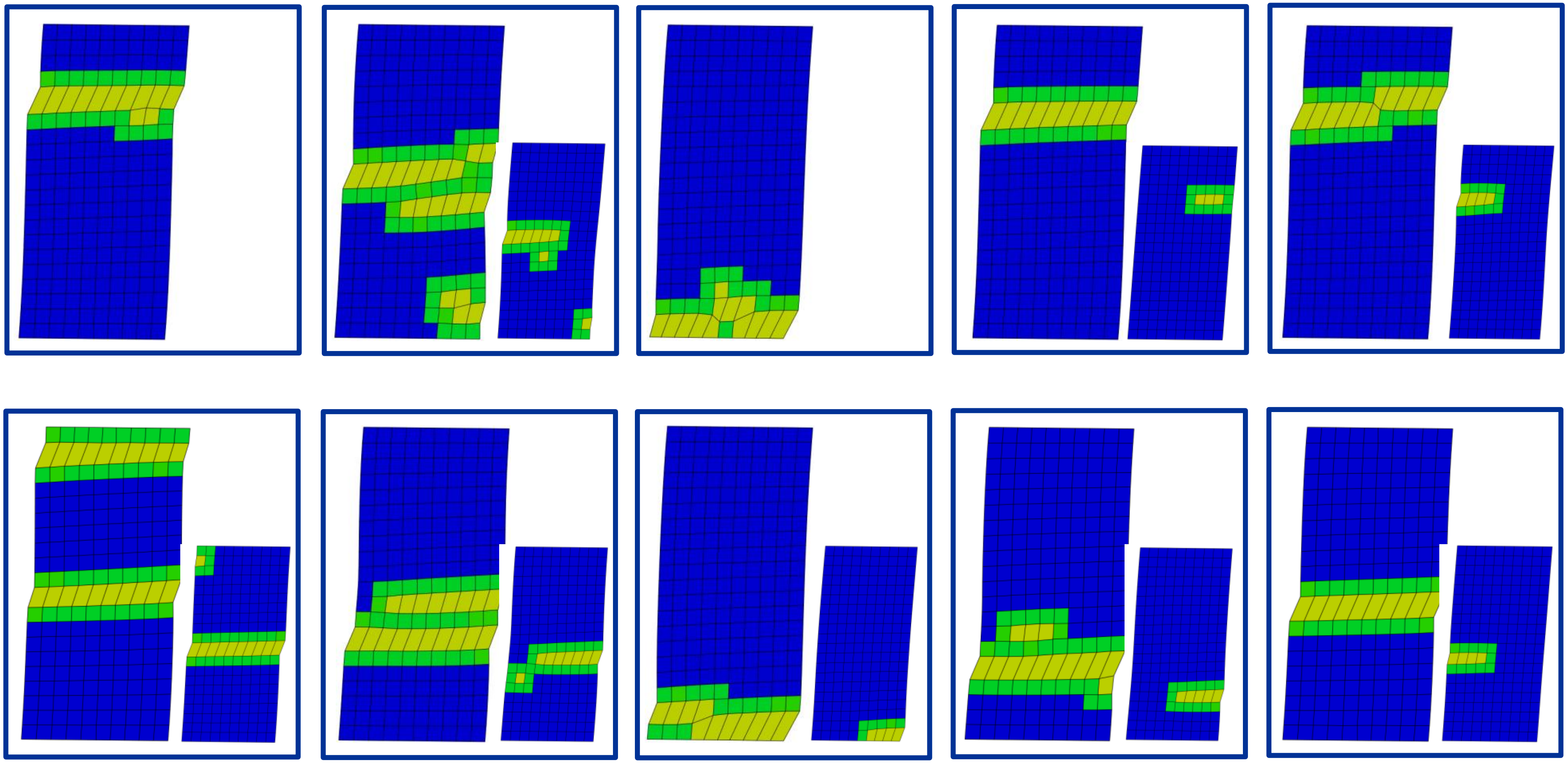


FEA of RUC



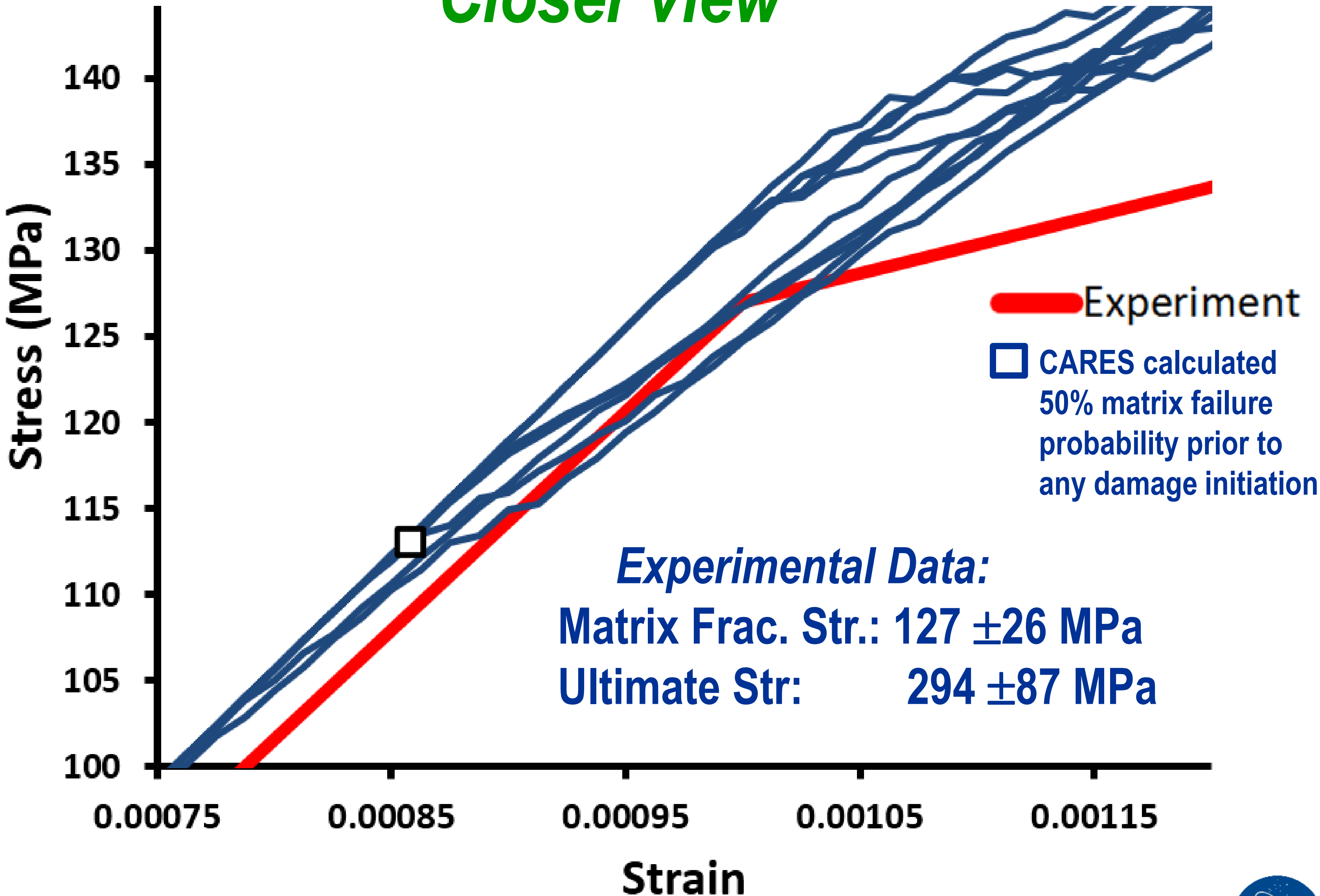
45^0 off-axis tensile specimen; 10 trials at final failure deformed plots

- Edges are allowed to freely deform (warp) on cool-down
- *After cool-down;* bottom edge fixed in loading direction when displacement load applied
- After cool-down; single node along top edge (middle) fixed in direction perpendicular to displacement direct.



Prediction for Ten Trials for $[0_2/90_2]_s$ Fiber Orientation

Closer view



Experimental Data:

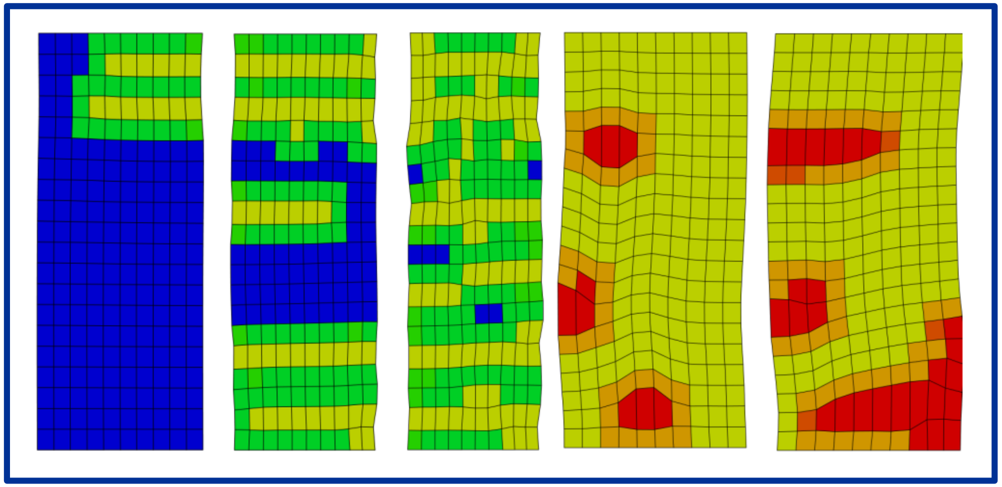
Matrix Frac. Str.: 127 ±26 MPa

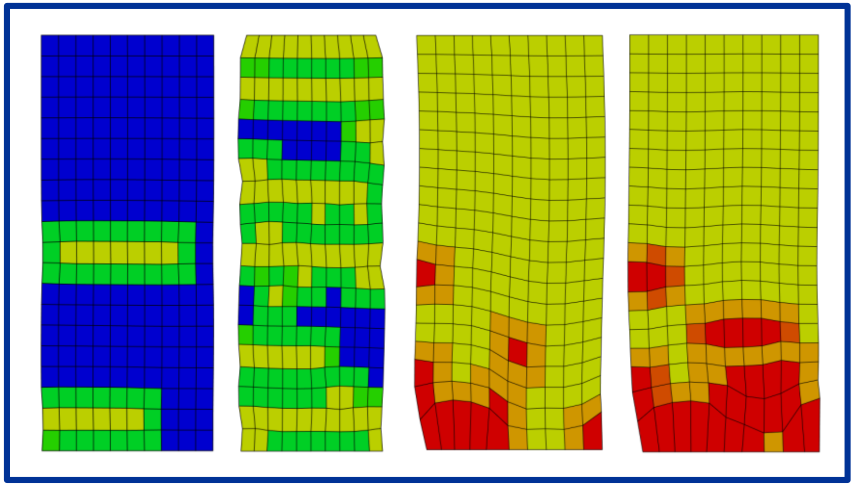
Ultimate Str: 294 ±87 MPa

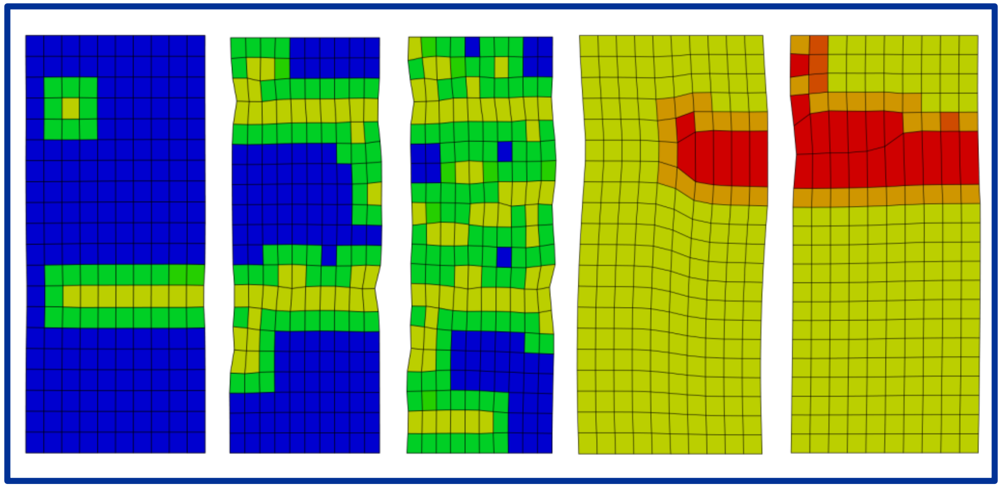
For $[0_2/90_2]_s$ fiber orientation; four trials with deformed plots

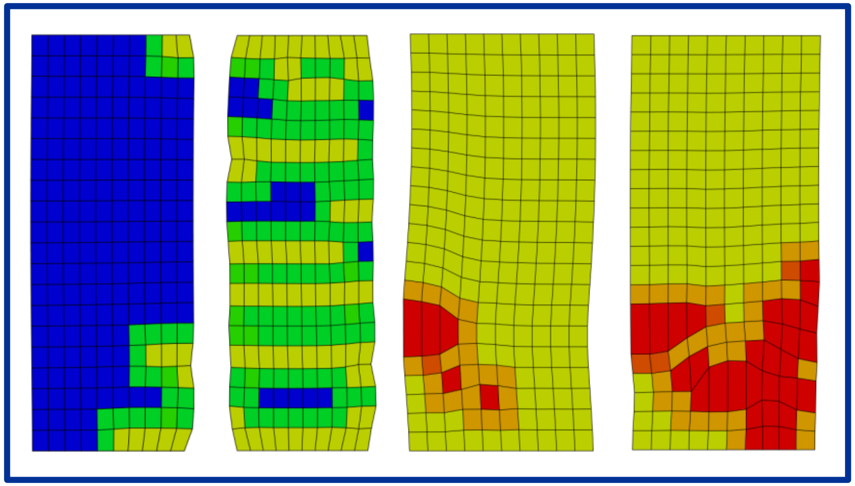
Progression from matrix failure to final fiber failure

FEAMAC/CARES analysis was for four plys (0/90/90/0) to speed computation









Path Forward

- Continue demonstrate/benchmark capability on CMCs *(using available literature)*
  - **For uniaxial & multiaxial failure response**
    (orientation, lamination, stress concentration, flexural)
    - Fast-fracture
    - Time & cycle dependent
    - more detailed micromechanical models of failure modes
- Develop / incorporate enviromechanical degradation models
- Investigate applicability to predict EBC damage progression
- Develop / incorporate anisotropic elastic modulus degradation based on CARES critical fracture angle probability density distribution
- Improve software efficiency (memory, speed, multiprocessing)

❖ **Demonstrate this capability on component/structure**

Approach For Life Prediction & Component Design Of Composites

➢ ***Combine CARES, MAC & FEA codes*** *where*
Micromechanics provides the link between structures & materials

CARES: *monlithic ceramics*

- Probabilistic strength
- Mechanistic-based multiaxial failure model
- Efficient life prediction algorithm
- Isotropic and *transverse isotropy*

New

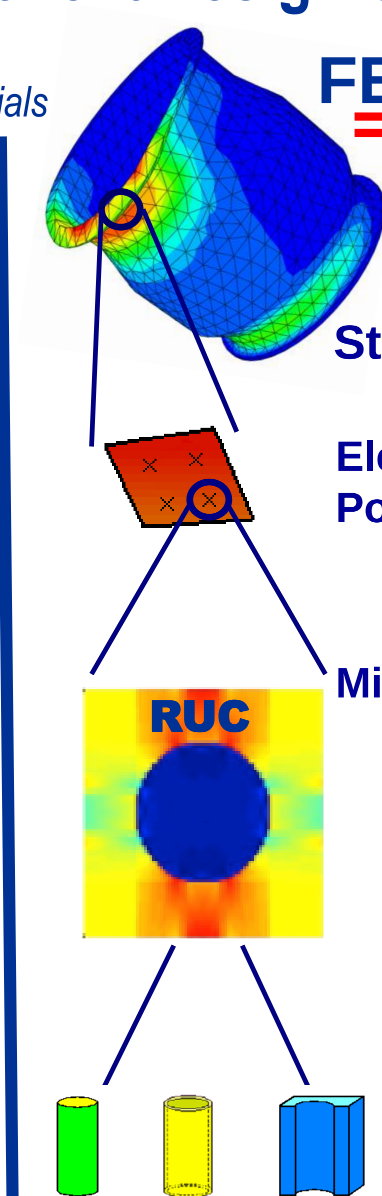
MAC/GMC: *composites analysis*

- Micromechanics
- Accurate RUC stress fields
- Flexibility in RUC designs
- Progressive damage capability
- Computationally efficient

Move CARES from the macroscopic scale of the structure to the microscale of the individual material constituents & RUC with the FEA-MAC micromechanics code

FEAMAC/CARES

(Abaqus UMAT)



Structural-Scale FEA

Element/Integration Point

Micromechanics Analysis

(MAC/GMC)

(CARES)
Subroutine

Reliability analysis at the RUC level